AN ASSESSMENT OF PRECISION TIME AND TIME INTERVAL SCIENCE AND TECHNOLOGY

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

AN ASSESSMENT OF PRECISION TIME AND TIME INTERVAL SCIENCE AND TECHNOLOGY

Committee for an Assessment of Precision Time and Time Interval
Science and Technology

Naval Studies Board
Division on Engineering and Physical Sciences

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Preface

The Department of the Navy strives to maintain, through its Office of Naval Research (ONR), a vigorous science and technology (S&T) program in those areas considered critically important to U.S. naval superiority in the maritime environment, including littoral waters and shore regions. In pursuing its S&T investments in such areas, ONR must ensure that (1) a robust U.S. research capability to work on long-term S&T problems in areas of interest to the Department of the Navy and the Department of Defense (DOD) is sustained, (2) an adequate supply of new scientists and engineers in these areas is maintained, and (3) S&T products and processes necessary to assure future superiority in naval warfare are provided.

One of the areas critical for the Department of the Navy is precision time and time interval (PTTI) science and technology. At the request of ONR, the National Research Council (NRC) established a committee, the Committee for an Assessment of Precision Time and Time Interval Science and Technology, under the auspices of the Naval Studies Board, to assess the S&T in this area. The terms of reference of the study called for the committee to review and assess the health of the existing Department of the Navy programs that contribute to PTTI, evaluate the Navy's research effort to develop capabilities needed for future clocks, identify non-Navy-sponsored research and development efforts that might facilitate progress in developing such advanced clocks, and recommend how the Navy's research program should be focused so as to meet future needs. The committee was asked to determine whether this task area meets the criteria for a National Naval Responsibility by assessing the following:

- Maturity of and challenges in key technology areas (including cost drivers),
- Interaction with related technology areas,
- Program funding and funding trends,
- Scope of naval responsibility,
- Scope, degree, and stability of non-Navy activities in key technology areas,
- Performer base (academia, government, industry, foreign),
- Infrastructure (leadership in the area),
- Knowledge-base pipeline (graduate, postdoctoral, and career delineation),

- Facilities and equipment, and
- Integration with and/or transition to higher budget category programs.

Two key questions for the committee were, What technology developments are needed to meet the Navy's long-term objectives? To what extent do these technology developments depend on Navy-sponsored R&D?

The committee was composed of individuals from a variety of backgrounds and organizations who are active in PTTI or related fields (see Appendix A). At its initial meeting, the committee received extensive briefings on the aims and accomplishments of the ONR research directed at PTTI, which is housed primarily in the Physical Sciences Division Code 331. This information was supplemented by additional information obtained through individual discussions with researchers and experts in the field. The committee's subsequent discussions of the existing program and its adequacy were based on information provided in those briefings and on the committee members' own experience.

The study began in December 2001 and lasted approximately 7 months. During that time, the committee held five meetings:

- *December 17-18, 2001, in Washington, D.C.* Organizational meeting with briefings provided by ONR, the Naval Research Laboratory (NRL), the U.S. Naval Observatory (USNO), the National Institute of Standards and Technology (NIST), the Institute for Defense Analyses, and Datum.
- *January 23-24, 2002, in Washington, D.C.* Briefings were provided by the Defense Advanced Research Projects Agency (DARPA), the Jet Propulsion Laboratory (JPL), the office of the DOD Director of Defense Research and Engineering, the National Reconnaissance Office, and researchers from Pennsylvania State University and the University of Washington.
- *February 26-27, 2002, in Irvine, California.* Briefings were provided by NIST, JPL, the Global Positioning System (GPS) Joint Program Office, the Department of the Navy's Space and Naval Warfare Systems Center (SPAWAR), and a researcher from the University of Colorado.
- *March 26-27, 2002, in Washington, D.C.* Briefings were provided by the Department of the Navy (OPNAV N70T/N60T), Frequency Electronics, Inc., and the Air Force Emerging Military Navigation and Timing Technology panel. (A scheduled briefing by Kernco was cancelled at the speaker's request.)
- *April 17-18, 2002, in El Segundo, California.* Committee deliberations and report drafting.

The resulting report, prepared in the ensuing several months, represents the committee's consensus view on the issues raised and questions posed in the terms of reference.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Anthony DeMaria, Coherent DEOS,
Norval Fortson, University of Washington,
Kurt Gibble, Pennsylvania State University,
Randall G. Hulet, Rice University,
Joseph J. Suter, Applied Physics Laboratory, Johns Hopkins University, and
Bruce Wald, Arlington Education Consultants.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by H. Gregory Tornatore, Applied Physics Laboratory, Johns Hopkins University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

Knowledge of time is essential to precise knowledge of location, and for this reason the Navy, with its need to navigate on the high seas, has historically played an important role in the development and application of advanced time realization and dissemination technologies. Discoveries coming from basic research funded by the Office of Naval Research (ONR) lie at the heart of today's highest performance atomic clocks, Naval Research Laboratory (NRL) expertise played a role in developing the space-qualified atomic clocks that enable the Global Positioning System (GPS), and the U.S. Naval Observatory (USNO) maintains and disseminates the standard of time for all of the Department of Defense (DOD). The Navy has made major investments in most aspects of precision time and time interval (PTTI) science and technology, although specific PTTI-related research has also been funded by the Defense Advanced Research Projects Agency (DARPA) and non-DOD agencies such as the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Department of Commerce. Navy funding, largely through ONR, has a history of being an early enabler of key new developments. Judicious funding decisions by the Navy—particularly by ONR program officers—have underpinned most of the major advances in PTTI science and technology (S&T) in the last 50 years. Chapter 1 describes the Navy's contributions to PTTI S&T (hereinafter referred to simply as "PTTI") in detail.

PTTI is important to modern naval needs, and indeed to all the armed Services, for use in both navigation and communications. Precise time synchronization is needed to efficiently determine the start of a code sequence in secure communications, to perform navigation, and to locate the position of signal emitters. Precise frequency control is required in communications for spectrum utilization and frequency-hopped spread-spectrum techniques. There are many examples of essential military operations that depend on PTTI and could benefit from improvements in PTTI technology. These include:

- GPS clocks and autonomous operations,
- Weapon system four-dimensional coordination,
- GPS antijamming,

- Network-centric warfare, and
- Secure military communications.

Realizing reductions in the size, weight, and power requirements and increases in the ruggedness of PTTI devices without sacrificing performance would put more accurate and precise timekeeping in the hands of the warrior, improving capabilities in all of the above operations. Chapter 5 discusses applications of PTTI techniques and devices to real military scenarios.

Research areas related to PTTI that, if pursued, should lead to improved military capabilities include the following:

- *Atomic, molecular, and optical physics.* Recent advances such as the realization of Bose-Einstein condensates hold promise for pushing the limits of our fundamental laboratory time standards.
- *Materials science.* Advanced materials can help isolate the high-performance elements of atomic clocks from environmental effects and reduce the size and weight of these devices. Materials advances will be necessary, for example, to successfully produce a chip-scale atomic clock.
- *Chemistry.* Advances that improve the availability of high-perfection quartz would have immediate impact on devices that currently rely on quartz crystal oscillators as clocks or as local oscillators. This includes most PTTI devices used by the DOD.

Chapter 4 discusses these and other research areas that can be pursued to advance DOD capabilities in PTTI.

The health of the U.S. PTTI infrastructure, discussed in Chapter 3, is mixed. The United States has been a leader in PTTI science and technology since at least the time after World War II, but in the last two decades its dominant position in PTTI has been eroded by increased foreign investment in PTTI sciences. University programs in atomic, molecular, and optical (AMO) physics and precision measurement produce sufficient numbers of scientists to enter PTTI work, but these researchers require 5 or more years apprenticeship after their formal studies before they become independently productive PTTI researchers. This is unlike the situation in several other countries, where there are special programs of study in key aspects of PTTI science and technology. Certain aspects of the U.S. PTTI infrastructure are in jeopardy, especially U.S. expertise in high-performance crystal oscillators. Industrial support for DOD needs in high-performance clocks and frequency standards is narrow and shallow. Most industrial firms focus their efforts on the much larger and less demanding low-performance commercial markets and could not readily shift their product development and production into high-performance devices, which are highly complex. The handful of firms that is capable of producing high-performance devices for defense purposes finds the demand for these devices to be too small and intermittent to support a business. Private industry currently has no incentive to conduct R&D related to high-performance devices suitable for military use.

Based on its analysis of the above factors and the current status of U.S. PTTI research and development, the committee has formulated a dozen findings and five associated recommendations.

NEED FOR PTTI

Finding: Accurate time and frequency have been, are, and will be critical to the Navy's (and indeed all of DOD's) warfighting capability.

PTTI has proven to be of enormous leverage in war fighting. Advances in a number of areas, including reduction in the size, weight, and power requirement of mobile devices, improved ruggedness of field systems, and better precision and accuracy for time dissemination, will lead to improvements in DOD capabilities that rely on PTTI. For example, rugged chip-scale atomic clocks with 10^{-11} accuracy would significantly improve networking and weapons system effectiveness by enabling better four-dimensional coordination of systems. Advanced GPS satellite clocks would greatly improve ranging accuracy, reduce collateral damage, and enhance system survivability. Reliable oscillators would improve the jamming resistance of GPS-guided munitions by enabling faster direct acquisition of the GPS signal in cases of jamming. Faster dissemination of command knowledge on the battlefield, combined with smaller, more precise weapons, would reduce collateral damage and thus reduce operational and political costs.

PTTI INFRASTRUCTURE

Finding: Internationally, the United States is an important player in PTTI research but no longer the dominant one.

Increased foreign participation in major PTTI conferences attests to the fact that the United States has more competition in PTTI research than in the past. Countries such as Australia, China, Finland, France, Germany, and Russia all train students specifically in PTTI technology.

Recommendation: While it is important to retain U.S. leadership in PTTI, ONR and USNO should consider whether opportunities exist to take advantage of growing foreign competence in PTTI by cooperating with allies. This might defray the cost of some current PTTI programs, freeing resources to pursue advances in other areas of PTTI.

Finding: Training in precision frequency control and timing per se is rare in the United States, and training in the fields relevant to PTTI is mixed—some is adequate, some is not.

In particular, there is a dearth of U.S. training opportunities in areas relevant to high-precision quartz resonators and oscillators, which play a key role in most applications that utilize PTTI in the field. There are a number of areas in which the performance of these oscillators could be improved, which would translate directly into improved systems for the warrior. Without researchers trained in crystal oscillators, the United States risks losing out on these advances in capabilities.

Finding: There is little incentive for commercial firms to produce PTTI devices for defense systems.

A large market for inexpensive quartz crystal oscillators exists for applications such as watches and other relatively low-precision consumer goods. The market for defense-quality quartz oscillators is miniscule in comparison with this lower quality market. The situation is similar for atomic clocks, with the largest market for moderate-quality clocks being commercial telecommunications. Relative to this market, the purchase of high-precision clocks for defense systems is infrequent and involves a small number of clocks.

Industry needs a steady source of funding to maintain production capability for precision frequency sources for special applications, such as space-qualified, severe environments and very small size and power requirements. In particular, without sustained support, precision quartz oscillators may no longer be available from U.S. sources.

PTTI AS A NATIONAL NAVAL RESPONSIBILITY

Finding: Past Navy funding for basic research in atomic and molecular physics has led to significant advances in PTTI.

For example, ONR was a supporter of the research that led to three Nobel Prizes in physics—Norman Ramsey in 1989, Bill Phillips in 1997, and Carl Wieman, Eric Cornell, and Wolfgang Ketterle in 2001. ONR-funded spectroscopic studies by Ramsey at Harvard University in the 1940s led to the design of the microwave cavity that remains an essential part of high-accuracy clocks today. ONR was an important early funder of work in the 1980s by Bill Phillips (at the National Institute of Standards and Technology (NIST)) in laser cooling and trapping of atoms, a technique that is at the heart of today's most accurate clock, the cesium fountain clock. These investigators all had as their primary goal advancing fundamental scientific understanding of the nature of nuclei, atoms, and molecules, but the judicious support of their research ideas by ONR program officers led to fundamental advances in PTTI as well.

Finding: The U.S. Navy has been the principal developer of advanced atomic PTTI technologies for DOD applications.

ONR funding was key to the development and commercialization of cesium atomic beam clocks, rubidium gas cell clocks, and the hydrogen maser. The NRL Timation project and subsequent Navy developments in satellite navigation and orbiting precision clocks led to today's GPS and led to NRL becoming the DOD's lead developer of advanced atomic clocks for space. USNO has been a key player in the development of precise time coordination and transfer techniques such as GPS common view, GPS carrier phase, and two-way satellite time transfer.

Finding: PTTI is a Critical National Defense Technology, and advances in PTTI that are most relevant to defense will only be developed under military sponsorship. PTTI is of benefit to all the Services and is essential to the Navy.

DOD has unique PTTI needs. These include applications operating under environmental extremes, with low power consumption and light, compact design, as well as clocks for autonomous submarine operation over long periods.

Finding: Only the Navy possesses the technical capabilities and has demonstrated the sustained interest in PTTI that will meet DOD needs for operational atomic clocks.

The Navy has always played a large role in PTTI. The depth and scope of its S&T budget for PTTI research over the past 30 years exceeds that of the Army and Air Force budgets. USNO is the designated agency for providing Coordinated Universal Time (UTC). Additionally, the Navy is recognized through DOD directive 5160.51 as the PTTI manager. The Navy has served as a resource for others in the DOD requiring PTTI. Traditionally, ONR has taken the lead in supporting research and development in PTTI owing to PTTI's critical importance for navigation.

While other services do fund PTTI-related research and development, certain aspects of PTTI depend directly on Navy capabilities and investments. These include but are not limited to the following:

- Maintenance of state-of-the-art atomic clock stability in space military environments,
- Maintenance of a fundamental time reference with at least an order of magnitude better timing accuracy than that used by any DOD application, and

- Global dissemination of precise timing signals for military use.

Recommendation: Based on the above considerations, the committee recommends that PTTI should be established as a National Naval Responsibility.

OPPORTUNITIES TO ADVANCE PTTI SCIENCE AND TECHNOLOGY

Finding: Significant opportunities to advance PTTI science and technology do exist and can be pursued if resources are directed at them.

Pursuit of advanced concepts such as concepts utilizing optical frequencies or coherent population trapping should improve the precision available today in laboratory atomic clocks by one or more orders of magnitude. Local oscillator improvements can be obtained by better understanding quartz crystal systems and by pursuing optoelectronic oscillators and other high-performance microwave oscillators. Materials development can improve the isolation of sensitive clock elements from noise and decrease the size and weight of devices, enabling higher-precision PTTI applications on the battlefield. Microelectromechanical systems (MEMS) and nanoscale devices may also enable smaller, lighter devices with higher precision than is currently available on the battlefield.

Finding: Some areas of science and technology important to DOD PTTI applications are currently given insufficient attention, such as research to improve synchronization, local oscillators, and the ruggedness of small, low-power clocks.

Researchers have achieved orders of magnitude improvement in the accuracy of laboratory time measurements in the last two decades. We do not yet have the capability to utilize this accuracy in fieldable systems, partly because of insufficient research devoted to areas critical to the development of operational devices and partly because research, especially applied research, is not being effectively transitioned into fieldable capabilities.

Finding: Continuity of programs is required to ensure that expertise is transferred from one generation of PTTI researchers to the next.

The technology underlying PTTI deals with a level of precision not found in most other technical areas. It places requirements on practitioners that cannot be learned without several years of training. No course of academic training can produce an accomplished PTTI scientist; rather, an apprenticeship of sorts is required, in which an early career researcher works side by side with an accomplished PTTI scientist to learn the nuances of producing real systems of incredibly high precision. For this reason PTTI expertise, if lost, could not be readily rebuilt and certainly not in a short (5-year) time frame.

Recommendation: ONR should stabilize its 6.1 funding of PTTI-related research at its current level or higher. Means should be sought to broaden basic research support beyond atomic, molecular, and optical physics so that it includes enabling advances in materials science, chemistry, photonics, and other relevant areas. Support for quartz crystal research is of particular importance.

Recommendation: To improve insertion of PTTI advances into DOD capabilities, ONR should increase 6.2/6.3 funding in PTTI, focusing on achieving improvements in ruggedness; decreasing the size, weight, and power consumption of PTTI devices; and developing new and improved techniques for precise time dissemination and coordination.

Finding: Coordination and planning of PTTI activities between the Services, with DARPA, and between DOD and other agencies is fragmented. Both internal and external guidance are needed.

Based on the committee's data gathering and on its members' experiences, there seems to be little coordination of PTTI research or development activities between the Services. Of particular concern is an apparent lack of the planning required to leverage advances at both the basic and applied levels to improve military system performance. Coordination between the Services and with DARPA would result in a quicker and more complete capture of the benefits that come from PTTI advances. Similarly, coordination between the DOD and other federal agencies with significant interest in PTTI technologies, such as NASA and NIST, could be strengthened.

The Department of the Navy, as the PTTI manager for DOD, currently has responsibility for coordinating the development of PTTI techniques among DOD components. Not only is PTTI broader than the Department of the Navy, it is also broader than any single Department of the Navy or DOD program. The committee could find no instance in which the PTTI program as a whole is regularly reviewed and no instances of previous external review. The committee is aware that the DOD PTTI manager convenes an annual review of advances in PTTI science; while this is useful, it does not replace review of the DOD strategy in PTTI. The committee believes that regular advice from external technical experts could help the Department of the Navy construct its investment strategy and address these problems of breadth and coordination.

Recommendation: The Director of Defense Research and Engineering (DDR&E) should coordinate PTTI research DOD-wide and develop an insertion plan to ensure that 6.2/6.3 advances in PTTI are transitioned into operational military systems. To help DDR&E and to ensure that the Navy's responsibilities as PTTI manager are met, the Department of the Navy should convene regularly (at least annually) an outside, independent group of experts to address DOD needs in PTTI and opportunities in PTTI research.

1

The Navy and PTTI

THE NAVY'S ROLE IN DEVELOPING PTTI

Naval operations and commercial shipping have been drivers for many technological developments in precision time and time interval science and technology (PTTI). In the Age of Exploration, the inability to determine longitude accurately made navigation on the open seas difficult and treacherous. Determining longitude required comparing the time at the current location with the time at a known location, say the Greenwich meridian. No shipboard clocks could determine time to an accuracy sufficient for navigational purposes. Heads of several seafaring nations offered great prizes for a solution to the problem of longitude. In the early 18th century, the Longitude Prize offered by Britain led to the development of the ship's chronometer. This device was so amazingly workable that it remained in use unchanged in its essential elements until the electronic era of the early 20th century.[1]

Following World War I and the development of the electronic oscillator and radio communications, the U.S. Navy took an ever more active role in the development of emerging PTTI technologies. The U.S. Naval Observatory (USNO), the Naval Research Laboratory (NRL) and, after World War II, the Office of Naval Research (ONR) were important players in the development of the technology that makes up the current state of the art in PTTI. Although the defense applications of PTTI now go well beyond navigation, the U.S. Navy has maintained its leadership role in the field. The discussion that follows highlights those events in the history of PTTI that have had significant Navy support.

Atomic Clocks

The advances that had been made in high-frequency electronics during World War II radar research set the stage for the development of atomic clocks.[2] In 1942 the Joint Chiefs of Staff established a

[1]The story of the search for a practical method of determining longitude at sea is told by Dava Sobel in *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time,* Walker and Co., New York, N.Y., October 1995.

[2]For a more complete discussion of the history of atomic clocks, see Norman F. Ramsey, "The Past, Present, and Future of Atomic Time and Frequency," *Proceedings of the Institute of Electrical and Electronics Engineers,* Vol. 79 (1991), No. 7, pp. 921-926.

Radio Propagation Laboratory at the National Bureau of Standards (NBS), now the National Institute of Standards and Technology (NIST). The Radio Propagation Laboratory developed the world's first atomic clock in 1948. This clock was based on the measurement of a spectroscopic absorption line in ammonia. Because its stability was no better than that of high-quality quartz oscillators, the ammonia system was quickly abandoned for the greater potential accuracy of the cesium atomic beam device. At the heart of this device, brought into operation at the NBS in 1951, was a microwave cavity design developed in 1948 by Norman Ramsey of Harvard University, with funding from the ONR nuclear physics branch. This cavity design and the interrogation method developed with it have proven so essential to high-accuracy atomic clocks that they remain part of all advanced clocks today. (Ramsey received the Nobel Prize for this work in 1989.)

The National Physical Laboratory of Britain (NPL) had developed this cesium beam standard into an operable clock by 1955. NPL then teamed with William Markowitz of the USNO to measure the frequency of the cesium transition relative to Ephemeris Time. The result of this measurement now defines the fundamental unit of time, the second. In a remarkable effort led by Jerrold Zacharias of the Massachusetts Institute of Technology and partially funded by ONR, in 1955 the technology of the cesium atomic beam clock was transformed into a commercial product, the Atomichron, at the National Company. The NRL took delivery of the first unit produced.

In the late 1950s the rubidium cell clock was developed at NBS. It was tested in collaboration with NRL, using NRL's Atomichron and a classified NRL microwave synthesizer that NBS researchers were not allowed to examine. This rubidium clock technology is the workhorse of our space-based clocks today. In 1960, with ONR funding, Ramsey developed the hydrogen maser. Subsequently, with funding and technical support from NRL, the hydrogen maser clock was brought into semicommercial production. Forty years later, this clock technology still produces the best short- to medium-term clock stability commercially available. These three clock types—the cesium atomic beam, the rubidium gas cell, and the hydrogen maser—make up the totality of our commercially available atomic clock technology.

Navy involvement has also been vital to the development of the most advanced laboratory atomic standards and the technology that will produce our next generation of high-performance atomic clocks. NRL funded the development of the buffer-gas-cooled mercury ion frequency standard at Hewlett-Packard. Several units were produced and delivered to the USNO. ONR funded basic research in the laser cooling of ions and atoms, which has led to our most accurate laboratory standards today—the cesium atomic fountain and the emerging optical clocks. (This work also led to the 1997 Nobel Prize in physics for Bill Phillips of NIST.) ONR-funded work in Bose-Einstein condensates (for which the 2001 Nobel Prize in physics was awarded to Eric Cornell of NIST, Carl Wieman of the University of Colorado, and Wolfgang Ketterle of the Massachusetts Institute of Technology) and the area of quantum entanglement is expected to find application in future, still higher performance atomic clocks.

Space Clocks, Timation, and GPS

Immediately following the launch of the first artificial Earth-orbiting satellite, Sputnik, by the Soviet Union in 1957, the Navy set up the Naval Space Surveillance System (NAVSPASUR) to track satellites, and shortly afterward a group at Johns Hopkins University's Applied Physics Laboratory (JHU/APL) began to track satellites by Doppler shift. Operated in reverse, this technique allowed simple two-dimensional navigation. The concept led APL to develop the first satellite navigation system, Transit, in the early 1960s, with Navy and Advanced Research Projects Agency (ARPA) funding. In 1964, Roger Easton of the NRL put forward a concept for an improved system that would

orbit precision clocks. Signals from such a satellite could provide more precise navigation as well as precise time signals that were available worldwide. To achieve this goal, NRL started programs to develop improved quartz frequency standards suitable for spaceflight. Soon thereafter, the Timation program, which involved atomic clocks in space, was established. These space-qualified atomic clocks were then used in the Global Positioning System (GPS). GPS became a joint Service program in 1973, with the Air Force designated executive agent for the system. NRL became a key participant in the development of advanced atomic clocks for flight in GPS satellites. This NRL program nurtured industrial development of space-qualified atomic clocks, developed alternative sources for clocks, supported advanced clock development, provided testing services for the space qualification of clocks, and, ultimately, provided an in-house expertise base from which all DOD space clock programs can draw.

Time Coordination

The USNO Time Service provided its first electrically delivered time signals in 1865, when a telegraph signal was used to synchronize clocks at a number of naval facilities. In 1904 the Navy was the first to broadcast a time signal via radio. In the World War II period, the Navy was involved in the development of radio navigation systems that used time of arrival of signals rather than a less precise radio direction method. These long-range navigation (LORAN) systems were used until recently for time transfer and coordination.

LORAN suffered from unknown time propagation delays that needed to be calibrated for the most precise uses. The Navy sponsored a number of flying-clock experiments to provide this calibration, among other things. Despite LORAN's limitations in precise time transfer, it was well suited for frequency comparison. In the late 1950s, in collaboration with Britain's NPL, USNO used the LORAN system to determine the frequency of the cesium transition relative to the Ephemeris second. In a similar experiment in the early 1960s, USNO and Varian Associates used the LORAN system to determine the frequency of the transition in the hydrogen maser.

The GPS system provides one of the best and the most ubiquitous time coordination systems ever.[3] Since the essence of the system is a time-encoded signal, it was a simple matter to use the system for time transfer. The USNO, in collaboration with various timing labs around the world, contributed to the development of the three most common ways to transfer time or time difference via the GPS system: the one-way, common-view, and carrier-phase techniques. The USNO also helped develop two-way satellite time transfer (TWSTT). TWSTT involves the use of communication satellites and active transmission from ground sites, making it complex and expensive to use. But it can give short-term stability for determination of time difference similar to GPS carrier phase and absolute time synchronization that may be better than GPS common view, and so is the method of choice for certain applications.

IMPORTANCE OF PTTI TO THE NAVY AND MODERN WARFARE

Warfare has always been four-dimensional. Both location (latitude, longitude, altitude) and time play a critical role in defense and battle. Highly accurate clocks and frequency sources are of vital importance to DOD, because the accuracy and stability of these devices are key determinants of the performance of command, control, communications, and intelligence (C3I); navigation; surveillance;

[3]For an overview of the Global Positioning System and its operations, see NRC Committee on the Future of the Global Positioning System, *Global Positioning System: A Shared National Asset*, Aeronautics and Space Engineering Board, National Academy Press, Washington, D.C., 1995.

electronic warfare; missile guidance; and identification, friend or foe (IFF) systems. DOD systems such as GPS, military strategic and tactical relay (MILSTAR), joint surveillance target attack radar system (JSTARS), Patriot, advanced medium-range air-to-air missile (AMRAAM), joint tactical information distribution system (JTIDS), and many classified programs are based on clocks with much greater accuracy and oscillators with much less noise than are required for commercial applications. The most precise methods of vehicle positioning and navigation rely on accurate time, and many aspects of communications (synchronization, encryption) rely on precise time.

From the general perspective of the DOD, precise time synchronization is needed primarily to efficiently determine the start of a code sequence in secure communications, to perform navigation, and to locate the position of signal emitters by means of time difference of arrival (TDOA), as is done, for example, in GPS positioning. Similarly, precise frequency control is required in communications, particularly for spectrum utilization and for frequency-hopped spread spectrum. Certain approaches to position location also rely on precise frequency determination. Frequency difference of arrival (FDOA) positioning techniques measure Doppler-induced frequency differences produced by a moving source and detected at spatially separated sites simultaneously or at a fixed reception site over time. The latter approach was used in the TRANSIT satellite navigation system. Conversely, FDOA can be based on frequency differences observed over time by a moving receiver locating a fixed source, as might be used in electronic intelligence activities. Finally, radars require precise frequency for moving target indication. DOD applications require increasingly precise time and frequency information distributed to widely separated sites, necessitating effective means of time and frequency dissemination; GPS is currently the most widely used means. These needs for PTTI are shared among the four Services, but the most precise requirements are those of the intelligence community.

While there are similarities between the PTTI requirements of the Services, there are also significant differences. The Army and the Marine Corps are oriented toward small size and very-low-power time and frequency devices to serve the needs of the soldier in the field. The Air Force has both space-based requirements, which are strategic, and aircraft-based requirements, which are tactical. Space-based applications of time and frequency devices demand long-term performance, environmental sensitivity, and reliable clock technology. Tactical applications usually have moderate performance requirements (in terms of stability and precision) but severe operating condition requirements, such temperatures from –55°C to +85°C and operation in high humidity or in highly dynamic environments requiring performance under conditions of acceleration and vibration. The Navy has both tactical (e.g., aircraft and ships) and strategic (e.g., submarine) needs and is unique in its need to communicate and synchronize between highly distributed assets.

Consideration of conflicts that the United States has participated in over the last 35 years illustrates the importance PTTI has on the battlefield. Many Navy pilots were lost in attempts to destroy a bridge over the Red River in North Vietnam during the late 1960s. Weapons could not be targeted precisely enough to destroy the target. In contrast, recent conflicts have seen tremendous reductions in casualties and new capabilities because of improved targeting. During the Gulf War, Iraq could not comprehend an attack from the featureless desert, but the famous End Run maneuver, enabled by GPS and atomic clocks, was exactly that. In Bosnia, GPS enabled all-weather and nighttime delivery of precise weapons. Local air defenses forced high-altitude delivery of the weapons, yet this enhanced weapon effectiveness, since there was more time for the guided munitions to acquire GPS signals. The media coverage of the Bosnian conflict enhanced sensitivity to collateral damage. This called for consideration of the bounded inaccuracy of weapons—an estimate of the bound on the probability of an event (for example, the probability of a weapon system miss beyond a certain distance from the target). GPS allows the

weapons operator to place usable bounds on this parameter, allowing bomb drops close to troops in contact with or near civilian targets, while avoiding fratricide or civilian casualties. Afghanistan continues the trend with weapons launched from long-distance, remotely piloted vehicles (RPVs). News photos have illustrated the awesome capabilities for precision strikes that have been enabled by precise timing capabilities.

Chapter 5 provides concrete examples of how PTTI affects the warfighter and what battlefield capabilities might be enabled by improvements in PTTI.

THE NAVY'S OPERATIONAL RESPONSIBILITIES IN PTTI

Navy responsibility in PTTI is currently designated in DOD Instruction 5000.2, Part 7, Section C, which calls for the Navy to

- Maintain the DOD reference standard through the USNO, and
- Serve as the DOD precise time and time interval (frequency) manager, with responsibilities for
  —Developing an annual DOD-wide summary of precise time and time interval requirements and
  —Coordinating the development of precise time and time interval techniques among DOD components.

SECNAV Instruction 4120.20 assigns responsibilities within the Department of the Navy for implementation of the Navy's responsibilities in PTTI. It names the Assistant Secretary of the Navy (Research, Engineering and Systems) as the Department of the Navy PTTI Coordinator and the Superintendent of the USNO as the DOD PTTI Manager. It further states that the Chief of Naval Operations shall program funds necessary to maintain the DOD reference standard and the means for dissemination to the accuracies required by the components and user agencies.

In addition to maintaining the DOD Master Clock for the DOD, USNO has an active research effort in clock development, time-scale algorithms, and time transfer through both GPS carrier phase and TWSTT. NRL maintains the Navy expertise in space clock technology, providing services and advice to Navy and DOD programs related to the space-based clocks used in GPS and other systems. NRL uses both in-house programs and commercial vendors to develop and test space clock technology. ONR sponsors basic research and development intended to enable future advances in PTTI technologies.

2

State of the Art of PTTI Physics and Devices

This section outlines briefly the basics of (1) frequency standards and clocks, discussing the standards currently available and those under development, (2) clock synchronization and syntonization, and (3) environmental effects on the performance of PTTI devices. A more thorough discussion of the science behind PTTI and more detailed descriptions of current standards are provided in Appendix B.[1]

BASIC DESCRIPTION OF FREQUENCY STANDARDS

A greatly simplified block diagram of an atomic frequency standard (also called an atomic clock) is shown in Figure 2.1. This consists of an atomic resonator, a local oscillator, and additional components. An atomic frequency standard produces an output signal whose frequency is related to an intrinsic atomic transition energy through Planck's constant. The atomic resonator frequency is generated from a local oscillator's frequency by frequency multiplication or frequency synthesis. The local oscillator frequency is locked to the frequency of the atomic resonator through the synthesizer and frequency multiplier with a servoloop time constant that is selected to provide optimum performance for the intended application. The atomic resonator determines the long-term stability of the standard; the local oscillator (also called the flywheel oscillator) determines the short-term stability.

Figure 2.2 shows the basic elements of a quartz crystal oscillator. Unlike the frequency of an atomic resonator, the frequency of a crystal oscillator is dependent on the properties of the individual crystal and how it is fabricated. Quartz crystal oscillators are used as clocks in those applications of PTTI in which some aspects of clock performance can be sacrificed to achieve devices of small size, low power, and light weight. Quartz crystal oscillators are also used as local oscillators for lower-performance atomic standards. High-performance laboratory atomic standards require higher-performance local oscillators such as the rubidium standard or the hydrogen maser.

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[1]An excellent introduction to the physics of time and time measurements, from early times to the modern day, is Claude Audoin and Bernard Guinot (Stephen Lyle, translator), *The Measurement of Time: Time, Frequency, and the Atomic Clock*, Cambridge University Press (English edition), New York, 2001.

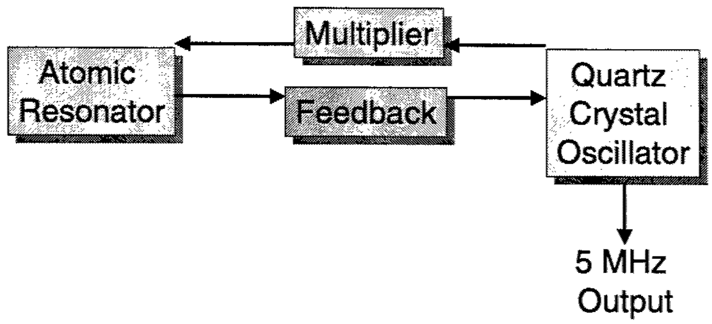

FIGURE 2.1 A simplified diagram of an atomic frequency standard.

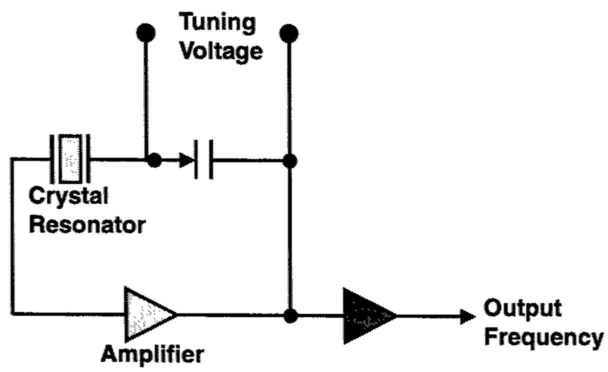

FIGURE 2.2 A simple circuit diagram showing the basic elements of a crystal oscillator.

PERFORMANCE OF FREQUENCY STANDARDS

The performance of any frequency standard, whether atomic or crystal, is described by three characteristics:

- Accuracy is a measure of how closely the frequency generated by the standard corresponds to its assigned value (e.g., the atomic transition frequency for an atomic standard). Accuracy can also be applied to a frequency measuring instrument, where it tells how close the instrument's reading is to the actual frequency being measured. A measurement of a 100-Hz frequency that is accurate to the sixth decimal place is said to be accurate to 1 part in 10^8, or to have 10^{-8} accuracy.
- Precision is a measure of the repeatability of a frequency measurement. It is generally expressed in terms of a standard deviation of the measurement.
- Stability is a measure of the maximum deviation of the standard's frequency when operating over a specified parameter range. Frequency aging, or long-term stability, is the slow change of the standard's frequency with time if all other parameters are fixed. Short-term stability is the deviation of the standard's frequency with time as the result of noise or other internal effects if other parameters are fixed. It is often expressed in terms of the Allan deviation (see Appendix D, Glossary).

CURRENT FREQUENCY STANDARDS

Atomic Frequency Standards

Cesium Beam Standard

These standards are based on measurements of atomic transitions in a beam of cesium-133 atoms. The accuracy of a laboratory cesium beam standard is typically about 1 part in 10^{14} averaged over one day. These frequency standards have been adapted for use in space, where some accuracy and short-term stability of the signal have been sacrificed to achieve ruggedness, reliability, small size, and low power requirements. There are currently five commercial suppliers of cesium beam standards, three of which are U.S. suppliers. These commercial standards vary in their accuracy, short-term stability, environmental effect on performance, and price, the best having an accuracy of a few parts in 10^{13} and an Allan deviation of about $8 \times 10^{-12}\tau^{-1/2}$. They are used as clocks in laboratories that contribute to the international atomic time scale, at the GPS ground control station that uploads time to the GPS satellites, and aboard Navy ships.

Cesium Fountain

These standards are also based on transitions in cesium-133 but differ from the cesium beam standards in that they probe collections of laser-cooled cesium atoms, which are launched upward like a fountain and probed during their free fall. This arrangement allows longer interrogation of the atomic transition. The longer interrogation time translates into a more accurate device, with fountain standards having an accuracy of about 1 part in 10^{15}. Cesium fountain standards are currently in use only in laboratories. They are being used by some laboratories to contribute to the international atomic time scale. Similar fountainlike, slow atom-beam devices are under development in both Europe and the United States for operation on the International Space Station (ISS).

Trapped Mercury Ion

In microwave-frequency trapped-mercury-ion standards, mercury-199 ions are confined using a radio-frequency quadrupole trap before probing a microwave-frequency ionic resonance. The large number of trapped ions probed increases the signal-to-noise ratio, and the long interaction time with the microwave radiation enables very good short-term stability (about $4 \times 10^{-14}\tau^{-1/2}$) if an extremely good local oscillator is used. This type of standard is currently installed in all three complexes of NASA's Deep Space Network and provides the highest stability of any standard in support of NASA missions. The GPS Joint Program Office has supported the development of a prototype spaceborne standard based on this linear ion trap standard (LITS) for future advanced GPS satellites.

NIST is developing a mercury standard using optical frequency transitions. This optical frequency standard is based on probing a single mercury-199 ion in a quadrupole trap; its potential for application is greatly enhanced by recent breakthroughs in optical frequency combs that link optical and microwave frequency sources (see discussion in Appendix B, "Connection Between Microwave and Optical Regions"). Probing a single ion using a highly stabilized laser source promises much better accuracy than current standards; an accuracy considerably better than one part in 10^{16} is expected to be achieved.

Hydrogen Maser

In current hydrogen maser (H maser) standards, molecular hydrogen is dissociated into atoms, which are state separated in a magnetic field so that the higher-energy-state atoms are directed into a bulb inside a microwave cavity resonant at the transition frequency. The interior of the bulb is coated to minimize the effects of atomic collisions with its walls. Nonetheless, although the short-term frequency stability of the hydrogen maser is excellent, its accuracy is inferior to that of cesium devices owing to wall-induced effects.

Research is ongoing on a cryogenically cooled hydrogen maser, which may be able to achieve frequency stability as good as 1×10^{-18}. There is also an ongoing effort to qualify a hydrogen maser for spaceflight. This unit has demonstrated Allan deviation stability of 5×10^{-15} at 100 seconds averaging time and weighs 100 kg. Ongoing programs in Switzerland and the United States seek to qualify H masers for extended operation in space.

There is presently one U.S. supplier of active hydrogen masers. Passive and active[2] hydrogen masers can be purchased from Russia. Hydrogen masers are finding increased use in time-scale ensembles owing to their excellent short-term stability.

Rubidium Gas Cell

The rubidium gas cell standard is based on rubidium-87 atoms sealed in a gas cell with a buffer gas. The buffer gas confines the rubidium atoms, thus largely preventing collisions with the cell walls. However, rubidium atom collisions with buffer gas atoms cause a pressure- and temperature-dependent frequency shift; another effect, the so-called light shift, is dependent on both the light intensity and spectral distribution of the lamp used to state select the atoms. Thus the rubidium gas cell standard has much poorer accuracy than the cesium beam standard and has frequency aging. However, its short-term stability can be very good if the standard is properly designed. In the laboratory, an Allan deviation of $1 \times 10^{-13}\tau^{-1/2}$ has been demonstrated, with perhaps an order of magnitude improvement possible.

Space-qualified rubidium gas cell standards are a modification of the laboratory device, with increased emphasis on small size, ruggedness, long life, and moderately good short-term stability. Rubidium cells flown on GPS block IIR satellites are providing better short-term stability than the cesium beam standards flown on earlier GPS satellites. Rubidium standards are also the principal timekeeping devices on MILSTAR military communications satellites.

Rubidium gas cells are by far the best selling commercial atomic standard. Commercial units are produced with an emphasis on low cost and moderately small size (~100 cm^3). They find use primarily in base stations for cellular telephone service and in other telecommunications applications.

Atomic Standards Under Development

Optical Standards Other Than Mercury

NIST is working on an optical frequency standard using trapped calcium atoms. Because the linewidth of the calcium transition is much larger than that of the mercury ion standard, the achievable accuracy is much poorer. However, the large number of atoms being interrogated in the calcium system gives a very good signal-to-noise ratio and, consequently, good short-term stability.

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[2]See Appendix B for a discussion of the difference between active and passive frequency standards.

A number of other ions and atoms are also under investigation as candidates for optical standards. Among these are single trapped ions of indium and ytterbium. Work is also being done on standards using trapped neutral atoms of strontium. Neutral atoms have the advantage that many can be held in the trap, giving a good signal-to-noise ratio and, consequently, good short-term stability. However, the transitions currently being investigated in neutral atoms have much larger linewidths than those of the ions, so the achievable accuracy is much poorer.

Coherent Population Trapping

Although discussed in the early 1970s, the coherent population trapping (CPT) approach has only recently received much attention, primarily because suitable lasers for pumping are only now available. Several groups are working in this field. The excitation of the atoms in this system is all optical, using two coherent optical signals to pump on two ground-state levels of the atoms. Unlike the other atomic standards discussed here, no microwave cavity is needed, so this device is potentially much easier to miniaturize.

Crystal Oscillators

The most common crystal oscillator is based on quartz. A quartz crystal acts as a stable mechanical resonator, which, by its piezoelectric behavior and high Q, determines the frequency generated in the oscillator circuit. The crystal resonator (also called the "crystal unit") is also the primary frequency-stability-determining element in the oscillator.

In the manufacture of quartz resonators, wafers are cut from a quartz crystal along directions precisely controlled with respect to the crystallographic axes. The properties of the device depend strongly on the angles of cut. After shaping the quartz to the required dimensions, metal electrodes are applied to the quartz wafer, which is mounted in a holder structure. The assembly is hermetically sealed, usually in a metal or glass enclosure. To cover the wide range of frequencies, different cuts vibrating in a variety of modes can be used.

There are three categories of crystal oscillators, based on the method of dealing with the crystal unit's frequency versus temperature (f versus T) characteristic. The uncompensated crystal oscillator, XO, does not contain means for reducing the crystal's f versus T variation. The temperature-compensated crystal oscillator, TCXO, uses temperature-dependent reactance variations to produce frequency changes that are equal and opposite to the crystal's temperature-dependent frequency changes—that is, the reactance variations compensate for the crystal's f versus T variations. Analogue TCXOs can provide about a 20-fold improvement over the uncompensated crystal's f versus T variation. Hysteresis, the nonrepeatability of the f versus T characteristic of the crystal, is the main TCXO stability limitation. The third category—the oven-controlled crystal oscillator (OCXO)—uses an oven to maintain the crystal unit and other temperature-sensitive components of the oscillator circuit at an approximately constant temperature. The crystal is manufactured to have an f versus T characteristic that has zero slope at or near the desired oven temperature. OCXOs can provide more than a 1,000-fold improvement over the crystal's f versus T variation. A special case of a compensated oscillator is the microcomputer-compensated crystal oscillator, MCXO, currently in advanced development. The MCXO minimizes the two main factors that limit the stabilities achievable with TCXOs: thermometry and the stability of the crystal unit. Instead of a thermometer that is external to the crystal unit, such as a thermistor, the MCXO uses a more accurate "self-temperature-sensing" method. To reduce the f versus T variations, the MCXO uses digital compensation techniques.

There is a significant commercial market for quartz crystal oscillators, but only the most high-end devices with the greatest stability are relevant to PTTI. Most of the commercial market is for low-end devices such as quartz watches and other consumer goods.

Optoelectronic Oscillators

NASA, DARPA, the Army, the Air Force, and NIST have invested in the development of a new approach for the generation of highly spectrally pure references. The approach, based on an opto-electronic feedback loop, provides the highest spectral purity at frequencies above 10 GHz by utilizing high-efficiency optical and photonic components in place of less-efficient microwave elements. A performance of 145 decibels relative to the carrier (dBc) at 10 kHz from a 30-GHz carrier has been demonstrated. A major feature of the optoelectronic oscillator (OEO) is that its design lends itself to miniaturization. A chip-based OEO can significantly reduce the cost, size, and power requirements and would be an important benefit for a number of ground, mobile, and space systems. Originally developed at JPL, the OEO technology was transferred to the commercial sector and is being advanced with private and government funds.

SYNCHRONIZATION AND SYNTONIZATION OF CLOCKS

A clock's time must be set initially to agree with some chosen time scale; this is synchronization. The clock's frequency must also be set so that its rate matches that of the chosen time scale; this is syntonization. An error in synchronization gives a time offset to the clock. An error in syntonization gives the clock a time error whose magnitude increases linearly with passing time (assuming the clock rates are constant).

There are four methods for synchronization and syntonization of high-performance clocks: GPS common view, GPS one way, GPS carrier phase, and two-way satellite time transfer.

GPS Common View

In GPS common view, observers at different locations receive the same time signal from the same GPS satellite and record the difference between their local clocks and the GPS time. Then by communicating their results and subtracting them, the GPS time drops out, with the result being the time difference between the local clocks. This result can then be used to synchronize the clocks. By using all the satellites in common view and averaging, the results can be improved. With well-calibrated receiver and antenna cable delays, the accuracy can be better than 10 nanoseconds. The stability of the measurements can be about 1 nanosecond. One uncertainty is the difference in ionosphere delays over the two paths. The Sagnac effect, due to Earth's rotation, and the relativistic effects of gravitational potential and of second-order Doppler must be taken into account in the measurement.

If measurements are made separated by some time, say 1 day, the change in time difference between the two measurements can be determined. This gives a measure of the rate, or frequency, difference between the clocks. The fractional frequency difference, $\Delta f/f$, is equal to the change in time, Δt, between the two clocks, divided by the time between measurements, t. This is the syntonization technique. With 1 nanosecond root mean square (rms) stability of the timing measurements, the accuracy of the $\Delta f/f$ determination in 1 day is about 1×10^{-14} rms. With averaging for 10 days, about 1×10^{-15} rms is achieved, assuming the clock rates are constant.

GPS One Way

If the position of a GPS receiver antenna is known, either by well-averaged GPS measurements or by survey, the user can determine the difference between the time of a local clock and that transmitted by the GPS satellite clock. This is known as GPS one way. Since the difference between satellite clock time and GPS system time is transmitted, the user can relate the local clock time to GPS time. The same is true for UTC (USNO) since that difference is also transmitted. The time difference accuracy can be about 10 nanoseconds over a day's averaging time if delays are well calibrated. The timing stability over 1 day can be 2 nanoseconds rms if UTC (USNO) is used with a good local clock and all satellites in view are observed. This gives a frequency accuracy of 2×10^{-14} rms averaged over 1 day.

GPS Carrier Phase

Monitoring the GPS carrier phase relative to the local clock can give frequency only since the actual cycle being tracked is unknown. The best results are obtained with post-processed ionosphere and orbit data. If the user keeps track of the signals as satellites come and go, averaging over 1 day the time stability can be better than 100 picoseconds rms, giving a frequency accuracy of 2×10^{-15} rms averaged over the day.

Two-Way Satellite Time Transfer

The two-way satellite time transfer (TWSTT) technique requires both sites to have two-way communications with the same geostationary communications satellite. Each site transmits a pulse from its own local clock and receives the pulse from the other site's clock. The time difference between the local clock pulse and the received pulse is recorded at both sites, and from those data and calibration of all the delays, many of which tend to cancel, the time difference between the local clocks at the two sites can be determined. The equipment for this method is moderately expensive, and satellite time must be scheduled and paid for, so this method is not as easy to use as the others. Time average accuracy ranges from 1 to 5 nanoseconds rms and time stability ranges from about 0.1 to 2 nanoseconds rms, giving a frequency accuracy at 1 day between 0.1 and 2×10^{-14} rms. Again, the Sagnac effect must be taken into account.

Table 2.1 summarizes the stability and accuracy of the available synchronization and syntonization technologies.

TABLE 2.1 Summary of Stability and Accuracy Available from Current Synchronization and Syntonization Technologies

Technology	RMS Time Accuracy (ns)	RMS Time Stability (ns)	RMS Frequency Accuracy 1 day	Comments
GPS one way	10 to 40	2 to 7	2×10^{-14}	Simple
GPS common view	1 to 10	1 to 2	$1\text{-}2 \times 10^{-14}$	Best GPS
GPS carrier phase	—	0.1	0.1×10^{-14}	Not in real time
TWSTT	1 to 5	0.1 to 2	$0.1\text{-}2 \times 10^{-14}$	Complex and expensive

ENVIRONMENTAL EFFECTS ON THE PERFORMANCE OF PTTI DEVICES

The accuracy and stability of a clock depends on its environment. A clock may have orders of magnitude higher stability in a quiet laboratory environment than in a military environment. The accuracy available for a given application also depends on the power and size the system allows for the clock. For example, small handheld systems cannot use atomic clocks, or even high-end quartz clocks, owing to size and power constraints.

Shock

The effects of moderate shock levels on quartz LOs include transient frequency offsets or, if mechanical damage is done, permanent offsets. Higher levels may break the crystal or its mounts. However, crystals have been designed and built to withstand being shot from a howitzer (16,000 **g**). Atomic standards can lose lock and fail if the transient effects are large enough in either the LO or the atomic resonator. In a passive standard used as a clock, if the LO has a step change in frequency due to shock or some other cause, the time output of the clock can have zero offset after the transient dies out if the loop filter contains at least two digital integrators.

Vibration

Vibration affects quartz LOs mainly through its acceleration effects on the resonator. Typical sensitivities of good quartz resonators are in the range of 10^{-9} to 10^{-10} per **g**. The effect is frequency modulation of the oscillator output. Sinusoidal vibration can cause disappearance of the carrier to an extent that depends on the vibration level and frequency. This effect can cause an atomic standard to lose lock and fail. If the vibration frequency is low compared with the reciprocal of the loop time constant in the standard, the LO frequency modulation due to the vibration will be reduced in the standard's output by the filtering action of the loop. Above the resonant frequency of the isolators, mounting the LO on vibration isolators reduces the effect.

Vibration can also modulate the output signal from atomic resonators. Vibration frequency at the interrogation modulation frequency can cause large frequency offsets or loss of lock. Fountain standards are particularly susceptible because the atoms in the fountain have low velocities.

Linear Acceleration

Good quartz resonators, as mentioned above, have sensitivities in the range of 10^{-9} to 10^{-10} per **g**. Using Mach's principle, this sensitivity is easily measured by rotating the oscillator 180 degrees relative to Earth's gravitational field for various initial orientations and measuring the frequency change due to the resulting 2 **g** change in acceleration. Acceleration can also affect the LO frequency indirectly owing to the resulting change in the temperature distribution or stress on the oscillator's electronic components.

Acceleration affects microwave atomic resonators by deforming and detuning the cavity. The effect is particularly severe in masers. Atomic trajectories in beam and fountain standards are affected by acceleration. The slower the atoms, the more severe the effect, so fountain standards are very susceptible.

Temperature

Temperature effects on quartz LOs have been mentioned above. For the precision LO applications, temperature control is usually necessary. The other types of LOs also require temperature control and/or compensation.

Temperature also affects atomic resonators. The frequency dependence on temperature due to buffer gas in rubidium standards is fairly large, but with moderate temperature control, the standard can perform at a few parts in 10^{10} over a fairly large temperature range.

The hydrogen maser has a frequency shift of -1.4×10^{-13} per degree C owing to the relativistic velocity effect. In addition, the cavity resonance for the maser is temperature sensitive, so that temperature control of the combined storage bulb and cavity is necessary. The magnetic field may also be temperature dependent.

In cesium beam standards, cavity detuning is important but much less so than in a maser. There can also be temperature effects due to changes in the gain of the beam tube and in the magnetic field. In the best performance standards, these effects are almost completely removed by digital monitoring and control of the microwave amplitude, magnetic field, and overall system gain.

Temperature effects in the advanced mercury-199 trapped-ion microwave standards are fairly small. Moderate temperature and magnetic field control are necessary.

Humidity

Humidity affects mainly the device's electronics, since the resonators, both LO and atomic, are sealed. Proper electronics design, with digital monitoring and control of important parameters, and proper construction can minimize the effect.

Magnetic Field

Quartz is diamagnetic; however, magnetic fields can affect magnetic materials in the crystal unit's mounting structure, electrodes, and enclosure. Time-varying electric fields will induce eddy currents in the metallic parts. Magnetic fields can also affect components in the oscillator circuitry, such as inductors. When a crystal LO is designed to minimize the effects of magnetic fields, the sensitivity can be $\pm 10^{-10}$ per gauss.

Microwave atomic frequency standards are particularly sensitive to magnetic fields because the hyperfine transition frequency that is the basis of the standard is proportional to the energy of the magnetic interaction between the outer electron and the nucleus. All these standards use hyperfine transitions with small quadratic magnetic-field dependence at the operating magnetic field of the unit—typically a few thousandths of a gauss. The sensitivity to field changes is smaller for large hyperfine transition frequency. Several layers of magnetic shielding provide a stable magnetic environment. Typical sensitivity for a shielded miniature rubidium standard is $\pm 2 \times 10^{-11}$ per gauss change in the external field. The best commercial cesium standards have external magnetic-field sensitivity of $\pm 10^{-14}$ per gauss, obtained by good shielding as well as digital monitoring and control of the magnetic field inside the atomic resonator.

The sensitivity of the hydrogen maser is about $\pm 3 \times 10^{-14}$ per gauss, obtained by good shielding.

Atmospheric Pressure

Ambient pressure changes can affect LO resonator frequency, causing changes in the deformation of the enclosure that affect the resonator through the mounting structure. They can also cause changes in the heat transfer, thus indirectly inducing frequency changes due to temperature variations. A well-designed quartz LO will change less than $\pm 5 \times 10^{-9}$ with a pressure change of 1 atmosphere.

Atomic resonators can also be affected by atmospheric pressure changes, either through direct

interaction or through indirectly inducing temperature changes. In rubidium gas cell standards, the gas cell deformation is pressure dependent, inducing buffer gas density changes. This produces frequency change of about $\pm 1 \times 10^{-13}$ per torr owing to increases in interatomic collisions. The hydrogen maser can be affected by "cavity pulling" if the cavity is not extremely well isolated from the pressure changes. The best commercial cesium beam standards change frequency less than $\pm 1 \times 10^{-16}$ per torr.

Aging

Aging is a slow change in frequency with time under constant ambient conditions. The best crystal LOs age less than $\pm 1 \times 10^{-10}$ per day. The effects of aging of the LO on an atomic standard can be virtually eliminated if the loop filter has at least two digital integrators.

Aging in rubidium gas cell devices can be due to changes in the buffer gas composition with time because of outgassing of the cell walls or helium diffusion. Another source of aging is change in the optical spectrum of the lamp and change in cell wall optical properties and the consequent change in pump spectrum with respect to the rubidium absorption spectrum, called the light shift. Typical aging in rubidium standards is $\pm 3 \times 10^{-13}$ per day.

Aging in the best commercial cesium standards is typically less than $\pm 1 \times 10^{-16}$ per day. Aging in hydrogen masers without cavity autotuning is on the order of $\pm 1 \times 10^{-15}$ per day, chiefly the result of slow changes in cavity dimensions. With cavity autotuning, $\pm 1 \times 10^{-16}$ can be achieved.

Retrace

Retrace is how well the standard or LO reproduces its frequency after a powerdown and cold restart. The best quartz LOs can retrace within a few parts in 10^{10}. Retrace of the best commercial cesium standards is about $\pm 1 \times 10^{-13}$. Retrace of rubidium gas cell devices is about $\pm 5 \times 10^{-11}$. Retrace of hydrogen masers is about $\pm 1 \times 10^{-13}$.

Noise

Frequency noise in quartz LOs is due partially to thermal noise in the resonator and noise in the sustaining amplifier. In addition, there are low-frequency sources of noise. One such source is temperature fluctuations, which cause frequency changes dependent on the temperature coefficients of the resonator and other sensitive elements. Another is called flicker, or $1/f$ noise, since its power spectral density is proportional to $1/f$, where f is the frequency of the noise spectrum being observed.

The atomic resonator in well-designed passive atomic standards determines frequency noise at times longer than the loop time constant. Atomic shot noise in beam standards and shot noise in the optical detector in gas cell standards are the primary source of frequency noise until flicker noise, with spectrum proportional to $1/f$, takes over at low frequencies or long times. The Allan deviation due to shot noise is proportional to $\tau^{-1/2}$, where τ is the averaging time. The Allan deviation due to flicker noise is independent of τ. Aging as well as low frequency noise more severe than flicker noise cause the Allan deviation to increase with averaging time.

A plot of Allan deviation, $\sigma_y(\tau)$, versus averaging time, τ, for several standards is shown in Figure 2.3.

Power Supply

Power supply variations can induce frequency changes in at least two ways. Residual voltage changes after imperfect voltage regulation cause shifts by means of voltage coefficients. LOs with voltage-variable tuning capacitors are particularly susceptible. Input voltage variations will cause variations in the power dissipated in the voltage regulators, and the resulting temperature changes can induce frequency changes.

Good quartz LOs have typical voltage coefficients of $\pm 5 \times 10^{-11}$ per volt. Rubidium gas cell devices are perhaps five times better. The best cesium beam standards will change less than $\pm 1 \times 10^{-13}$ over the full voltage range.

Radiation

In space-based clocks, radiation effects are a significant determinant of clock performance and lifetime. Background radiation particularly affects the performance of the quartz crystals, whether they are used as clocks or as the LO, by inducing defects in the crystals over time.

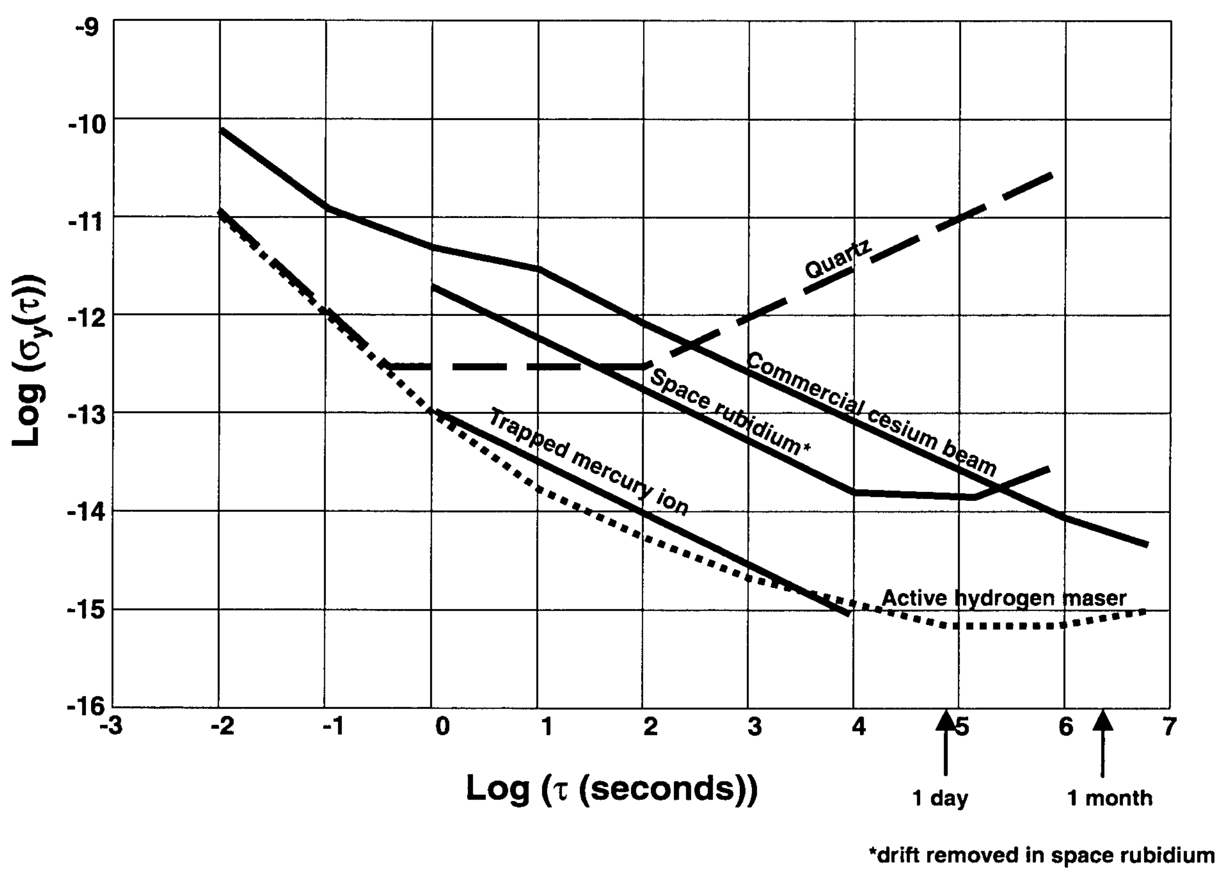

FIGURE 2.3 Short-term stability of some state-of-the-art standards.

3

State of PTTI Research and Infrastructure

HEALTH OF THE BASIC RESEARCH BASE

Historically, research in areas such as atomic and molecular physics, quantum optics, and solid-state physics, as well as in fields of technology such as photonics and material sciences, has played a key role in advancing the state of the art in PTTI. In particular, the tie between fundamental research in atomic, molecular, and optical (AMO) physics and advances in both state-of-the-art timekeeping and eventual performance improvement in what might be termed commercial-quality devices has been demonstrated over decades and is anticipated to continue for the foreseeable future.

Domestically, support for these basic investigations is provided by government organizations like NSF, DOE, NASA, DOD, and the Department of Commerce (NIST), while counterpart foreign organizations worldwide nurture similar studies. The Navy's role in promoting AMO physics basic research is as a highly targeted yet not dominant source of funding. For example, in FY 01, NSF spending on AMO physics[1] was approximately $8 million compared with ONR core expenditures of approximately $2.8 million on both its Atomic and Molecular Physics program and its Lasers and Electro-optics program and NASA expenditures of about $13 million on AMO and clock-related research in its Fundamental Physics program. Although proportionately a smaller contributor in FY 02 to the overall area of AMO physics research, Navy resources, provided through ONR, have paid excellent dividends by enabling advances of great relevance to PTTI, including investigations into the cooling and trapping of atoms, the development of atomic fountain frequency standards, and, more recently, Bose-Einstein condensation. Navy 6.1 support of basic research is significant for advancing the cutting edge of knowledge, as the prior successes of such research have shown. But more importantly for the Navy, these funds are highly leveraged through their judicious application to aspects of AMO physics that can be anticipated to have relevance to PTTI and other areas of Navy interest.

[1]Information collected at the National Science Foundation Web site, <https://www.fastlane.nsf.gov/a6/A6QueryPgm.htm>.

TABLE 3.1 ONR Funding for 6.1 and 6.2 Support of PTTI (million dollars)

Year	Atomic and Molecular Physics	Meteorology and Oceanography	Navigation Program	Total
6.1 funding				
1990	2.5			2.5
2002	2.0			2.0
6.2 funding				
1990				1.6
1995		1.6		1.6
1999		1.3		1.3
2001		1.0	0.7	1.7
2002		0.3	1.0	1.3

NOTE: These numbers are the approximate dollars spent from each program in PTTI; PTTI does not have its own program budget, and ONR was able to provide only estimates of the amount of these programs that was directed toward programs that could be characterized as PTTI.

Over the last 5 years, however, ONR funding to AMO physics investigations has not been stable. There has been a monotonic decrease in this support in then-year dollars, which becomes even greater when translated into constant dollars (see Table 3.1). This is telling, particularly because overall Navy 6.1 funding increased during those years, even in constant dollars.[2] Should this decrease in support continue, the productivity of the program would continue to decline. Because fundamental research entails a long-term investment, the impact of this reduction would not be immediately apparent; over time, however, its effects will be felt in the slowed progress of PTTI-related science and, probably more important, in a smaller pool of scientifically trained personnel who can meet military needs in the field. Given the importance of PTTI to Navy and DOD warfighting capabilities and the unique role the Navy plays in PTTI for all of DOD, the committee believes it is shortsighted to reduce the Navy's support of the basic research that has for so long led to advances in the field, improved PTTI performance, and supplied a cadre of technically knowledgeable individuals to satisfy the PTTI needs of Navy and DOD programs.

Only if the Navy 6.1 AMO physics research program maintains a close relationship with the research and development community can it support long-range research, foster the discovery of technologies, and nurture the next generations of researchers for the future Navy and Marine Corps. At present, ONR funds nearly 30 projects in AMO physics. The supported projects are well attuned to Navy mission goals, with many clearly relevant to the state of the art of PTTI. By their very nature, though, fundamental investigations proceed over many years. Training at the Ph.D. level often requires more than 5 years of graduate study, and particular projects may extend over multiple generations of graduate students before coming to full fruition. With this in mind, the committee believes that stable, multiyear funding of the research programs should be given the highest priority, including stability of the research funding overall and stability of funding to specific researchers. Ultimately, stable funding will ensure the greatest return on the Navy investment in basic research related to PTTI.

[2] Information obtained from the American Institute of Physics Web site, <http://www.aip.org/enews/fyi/>.

TABLE 3.2 Approximate Worldwide Annual Market for PTTI Devices

Technology	Units per Year (approximate)	Typical Unit Price ($)	Worldwide Market, ($/year) (approximate)
Quartz crystal	2×10^9	1 (0.1 to 3,000)	1.2 billion
Atomic frequency standards			
Hydrogen maser	10	200,000	2 million
Cesium beam	500	50,000	25 million
Rubidium cell	50,000	2,000	100 million

HEALTH OF THE APPLIED RESEARCH BASE

Industrial Base

Although there is a significant industrial base in the United States for PTTI technology, with well over 100 companies manufacturing and/or selling time- and frequency-related products, most of it focuses on relatively low-performance commercial applications. Table 3.2 lists the approximate worldwide market for PTTI devices. Because of performance or ruggedness requirements, most commercial products are not suitable for military or space applications. Though a company with a significant commercial base is theoretically well placed to move into military or space products, it would take a number of years and a significant investment of resources for a company producing products for the civilian market to develop and produce a suitable military product. Companies that have no experience in building high-precision frequency products but decide to enter the field will probably find entry to be considerably more difficult than they had anticipated. Presentations[3] to this committee by industrial suppliers of PTTI products indicate that there is little incentive for such suppliers to make the sustained investment necessary to produce defense-specific PTTI products, as the defense market is historically too small and inconsistent compared with the civilian market.

The capacity of U.S. industry to produce space-qualified atomic frequency standards and high-precision quartz oscillators is extremely limited. There are only four manufacturers capable of producing space-qualified atomic frequency standards (Datum, Frequency Electronics, PerkinElmer (formerly EG&G), and Kernco, Inc.). It is possible that this list could shrink to only one or two companies. Presently only one company (Datum) makes hydrogen masers, and these are not space qualified. The best high-performance quartz oscillators are now made in Europe. The market for all these high-performance products is very small and inconsistent. In general, the lack of sustained government support and stiff competition from overseas has resulted in relatively little U.S. industrial research and development in high-performance standards. Inconsistent funding has also made it difficult for companies to train and maintain a skilled engineering staff.

DOD Support of Applied PTTI Investigations

The development of PTTI products meeting military requirements has come almost exclusively as a result of DOD support. Because of PTTI's critical role in providing enhanced operational capabilities,

[3]Michael R. Garvey, Datum Corp., briefing to the committee on December 18, 2001; Martin Bloch, Frequency Electronics, Inc., briefing to the committee on March 26, 2002.

the importance to the Navy and the entire DOD of supporting their development cannot be overestimated.

There are numerous past and current examples of PTTI-related investigations producing capabilities of operational value to the military. The microcomputer-compensated crystal oscillator (MCXO), for example, is attributable entirely to Army 6.2 investment. This device produces frequency stabilities and accuracies rivaling oven-controlled crystal oscillators while requiring only a small fraction of the operating power, and it is finding use in applications as diverse as navigational buoys and GPS receivers. Army applied studies have also developed many processing techniques that are widely used in the manufacture of precision quartz resonators, such as UV-ozone cleaning, chemical polishing, and polyimide bonding. Programs executed by NRL in support of GPS have made major contributions to advancing the state of the art of atomic clocks for space applications. The development of a fountain clock capability at USNO is also serving to train scientists in the operation of these rather complicated standards, which someday may be the primary contributors to the DOD Master Clock. ONR 6.2 is supporting the development of coherent population-trapping frequency standards and the double-bulb rubidium maser, both of which are aimed at greatly reducing clock size for ultimate use in tactical devices. DARPA has initiated a program to develop a chip-scale atomic clock whose precision would be intermediate between that of current quartz crystals and large-scale atomic clocks.

While these DOD programs, taken together, represent a large amount of funding for PTTI research, coordination between them is lacking.

Very little work was presented to the committee in the area of synchronization and timing dissemination technology. Programs in satellite timing modems have ended, and inadequate resources are being spent on developing optical synchronization techniques, precision timing aspects of optical-to-electrical and electrical-to-optical conversion, improved PTTI metrology, frequency synthesis, methods for embedding timing in existing communications systems (e.g., LINK-16), methods for synchronizing and syntonizing satellites, methods for overcoming ionospheric and tropospheric transmission uncertainties, and other problems limiting the ability of remote users to communicate time and frequency. Synchronization and global time dissemination, which are important for achieving military applications of PTTI, do not appear to be receiving appropriate attention.

Quartz crystal oscillators, key components of the majority of atomic frequency standards and important time and frequency control devices in their own right, are not receiving Navy R&D funding. While there is Army support in this area, the committee finds aggregate support for crystal technology inadequate and interservice coordination lacking.

The desire to reduce the size of atomic frequency standards is putting greater emphasis on specific aspects of device design. For example, as the cells that store the atomic species upon which the devices are based become smaller, collisions between these species and the walls of their storage containers become more frequent and more important to overall performance. Advances in small-scale devices require an understanding of these collisional interactions and the development of mitigating techniques such as wall coatings. Progress in this and similar areas requires research in fields beyond AMO physics, such as material sciences and chemistry. Such research is lacking at both the fundamental level and, particularly, the applied level.

Over the last several years, aggregate ONR funding for PTTI applied research has fluctuated between $1.3 million and $1.7 million, with FY 02 funding at $1.3 million (see Table 3.1). These fluctuations hurt continuity in development programs. Moreover, they occurred during a period of continuing growth in Navy 6.2/6.3 allocations, raising questions about the priority the Navy gives PTTI investigations. Perhaps the greatest weakness in the support for applied PTTI studies is the lack of a true funding focus. The present approach to support, extracting funds from the meteorology and

oceanography and navigation programs rather than funding a PTTI-specific program, does not place the appropriate emphasis on PTTI studies. The resulting variability in support does not guarantee the continuity of effort that would maximize the probability of project success.

A plan is needed for inserting PTTI developments into defense applications. Simply increasing the funding for PTTI science and technology will not ensure improved performance for government users. There are several examples of situations in which large increases in funding did not result in the desired capability. For example, the Navy spent approximately $23 million in the 1970s and 1980s to develop flight-qualified hydrogen maser technology that would support the perceived need for 180-day satellite autonomy. The window of opportunity (GPS Block I) and the need both passed before success could be achieved, and the resulting technology has found no other military application. As another example, the Navy invested in development of alternative vendors for GPS flight clocks. EG&G and Kernco were supported for development of rubidium and cesium clocks, respectively. The cesium clock technology developed by Kernco was not used in GPS IIR despite its superior long-term on-orbit performance, because of technical problems with the large vendor chosen to manufacture the clock. These examples illustrate the importance of developing an effective PTTI insertion plan for the transitioning of research developments into operational capabilities.

HEALTH OF THE RELEVANT EDUCATIONAL BASE

There is a significant amount of on-the-job training required for all persons entering the precision time and frequency fields. The design and manufacture of atomic frequency standards (clocks) and other precision frequency standards, including quartz oscillators, must be addressed using a systems approach. That is, a frequency standard must be thought of not just as an electronic circuit (thermal and flicker noises, power levels, etc.), but also as a thermal system (static and dynamic sensitivities) and a mechanical system (vibration, static stress, stress relaxation, etc.). Its material characteristics (packaging, aging, wall coatings, etc.) and sensitivity to environmental parameters (temperature, humidity, pressure, acoustics, vibration, electric and magnetic fields, etc.) must also be taken into consideration, and, for practical devices, their cost, size, and power consumption. Nearly every factor has a potential impact on frequency when designing a product that has a stability or accuracy at levels approaching 1×10^{-15} or beyond—relativistic effects become everyday realities, and an act as simple as soldering the lead of a transistor to a circuit board generates a change in the magnetic field that affects the atomic transition frequency, for example. Thus, extensive experience is needed to develop the unique and broad set of skills for understanding the many parameters that are crucial to a successful precision frequency standard.

Very few U.S. institutions train students specifically in clocks or precision frequency sources. Other countries, such as Australia, China, Finland, France, Germany, and Russia, train students specifically in precision frequency control and timing. In the United States a number of groups train students in atomic physics and associated precision measurement, and these students can move relatively easily into work on atomic clocks. Table 3.3 names 13 universities in the United States currently receiving PTTI-related funding from ONR. Many of the engineers and scientists now working on atomic clocks came from these schools. Regardless of their university training, virtually all new industry and government hires in the United States must be trained by their employers in PTTI technology. Given the level of sophistication this work involves, it typically takes 5 to 10 years for a person to become fully productive.

A number of national laboratories or government-supported institutions train new scientists and engineers in atomic clock technology. Over the last decade the Time and Frequency Division of NIST, in conjunction with the University of Colorado, provided some level of training to more than 30

TABLE 3.3 Universities in the United States Receiving ONR 6.1 Funding in Areas Broadly Related to PTTI

University	Research Being Funded
California Institute of Technology	Information dynamics in open quantum systems
Florida International University	Atom optics with dark hollow beams
Massachusetts Institute of Technology	Studies of Bose-Einstein condensation; optical metrology with cold trapped hydrogen; atom interferometry
Princeton University	Optimal control of chemical reactivity in the strong field regime
Rice University	Quantum degenerate gas of fermionic atoms; creation and manipulation of quantum degenerate atomic strontium
Stanford University	Studies of electromagnetically induced transparency and its relation to nonlinear optics
State University of New York, Stony Brook	Cooling and trapping of neutral atoms
University of Arizona	Quantum dynamics of small atomic Bose-Einstein condensates; nonlinear manipulation and control of matter waves
University of Colorado	Bose-Einstein condensation and optical traps; ultracold gas of fermionic atoms; fiber atom optics
University of Oklahoma	Study of Bose-Einstein condensates using perturbation theory
University of New Mexico	Quantum logic with neutral atoms in traps; quantum nonlocality and entanglement
University of Rochester	Quantum degenerate atomic mixture vapors
Wayne State University	Optimal control of chemical reactivity in the strong field regime

undergraduate and Ph.D. students and 40 postdoctoral students. In the same time frame, JPL, in conjunction with the University of Southern California and the University of California at Riverside, supported more than 20 undergraduate students, approximately 5 doctoral students, and 10 to 15 postdoctoral students. Other institutions that have supported students or postdocs are the Harvard-Smithsonian Astrophysical Observatory, NRL, USNO, and the Aerospace Corporation. The situation is much worse for quartz resonators and oscillators. A few programs, such as one at the University of Central Florida, study acoustoelectronic technology. There is also some ongoing research on resonator characteristics at Rutgers University and Rensselaer Polytechnic Institute. However, there is no training in precision quartz oscillators at U.S. universities.

STANDING OF THE UNITED STATES IN INTERNATIONAL PTTI RESEARCH

To discern the trends in PTTI technology in U.S. institutions, and also to compare them with those in institutions outside the United States, presentations at PTTI Systems and Applications Meetings[4] and papers published in the Proceedings of the IEEE International Frequency Control Symposium (IEEE-IFCS) were surveyed. (These are the leading symposia for PTTI technology.)

The results of the surveys are summarized in Tables 3.4 and 3.5. Table 3.4 compares U.S. and foreign contributions. The PTTI symposia are held in the United States and are sponsored by the USNO, NRL, NASA-JPL, the Air Force Office of Scientific Research, the Defense Information Systems Agency, the Army Research Office, and the Coast Guard Navigation Center. An average of 43 percent of the presentations came from abroad between 1999 and 2001. By comparison, early PTTI meetings in the 1970s were dominated by U.S. contributions.

Table 3.5 lists the affiliations of authors (industry, university, national laboratories, military and military laboratories, or collaborations between these groups) of presentations from the United States

[4]Detailed information and abstracts can be obtained at <http://tycho.usno.navy.mil/ptti.htm>.

TABLE 3.4 Origin of Papers Presented at PTTI Systems and Applications Meetings

Year	U.S. Papers	Foreign Papers	U.S. and Foreign Collaboration	Total Papers
1999	31 (46 percent)	32 (48 percent)	4 (6 percent)	67
2000	30 (58 percent)	19 (37 percent)	3 (6 percent)	52
2001	37 (59 percent)	23 (37 percent)	3 (5 percent)	63

TABLE 3.5 Affiliation of Authors of Papers Presented at PTTI Systems and Applications Meetings

Year	Industry	National Laboratories[a]	Universities	Military and Military Laboratories[b]	Collaboration Between Industry, Laboratories, and Universities	Total Papers
1999	11 (16 percent)	4 (6 percent)	0 (0 percent)	10 (15 percent)	10 (15 percent)	35
2000	8 (15 percent)	5 (10 percent)	0 (0 percent)	12 (23 percent)	8 (23 percent)	33
2001	12 (19 percent)	7 (11 percent)	3 (5 percent)	14 (22 percent)	4 (6 percent)	40

NOTE: Data include only authors of papers from U.S. sources or from U.S.-foreign collaborations.
[a]National laboratories include NIST, JPL, and LLNL.
[b]Military and military laboratories include USNO, NRL, USAF, DOD, and DOT.

and from U.S. and foreign collaborations. Surprisingly, only 3 of 108 presentations are affiliated solely with U.S. universities. One-third of the papers came from the military and military laboratories. Box 3.1 lists the U.S. presenters. Box 3.2, which lists the foreign contributors for the symposia held in 1999 and 2000, illustrates the international breadth of PTTI research. Contributions were made by 22 countries. It should particularly be noted that significant contributions have been made in France to cesium fountain clocks and quartz resonator technology.

The results for the IEEE-IFCS symposia are summarized in Table 3.6. The top half of the table shows the average number of papers published in 1991 and 1992. The bottom half of the table shows the same information averaged over 2001 and 2002, a decade later. The papers are divided into acoustic technology (quartz oscillators, quartz resonator design or manufacture, acoustic materials (not just quartz), filters, surface acoustic wave devices, acoustic sensors, etc.) and nonacoustic technologies (atomic frequency standards, time transfer, microwave oscillators, synthesizers, phase noise characterization, stability analysis, etc.). The papers are also broken down into origin (from U.S. institutions and from non-U.S. institutions according to lead author). The institutions are categorized as universities, government laboratories, and industrial laboratories.

One important observation from these data is that the total number of papers has gone up by 43 percent over the last 10 years. About half of the increase came from acoustic sensor papers, which increased from one or two a year in 1991 and 1992 to about 20 each year in 2001 and 2002. The acoustic papers have no direct relation to PTTI technology. Also, three or four manufacturing technology papers have been added each year since the Piezoelectric Devices Conference and the IEEE-IFCS merged in 2000. Though the total number of papers has increased, the number of contributions from U.S. institutions has decreased by about 15 percent. This is in contrast to a 133 percent increase in papers from non-

BOX 3.1
U.S. Participants at the 1999 and 2000 PTTI Symposia

Aerospace Corporation, Los Angeles, Calif.
Agilent Laboratories, Palo Alto, Calif.
Agilent Technologies, Santa Clara, Calif.
Antoine Enterprises, Washington, D.C.
Bellaire Designs, Broomfield, Colo.
Boeing Space and Communication Services, Schriever Air Force Base, Colo.
California State University, Fullerton
Datum, Inc., Beverly, Mass.
Department of Transportation, Washington, D.C.
FAA/ISI, Vienna, Va.
Highland Technology, San Francisco, Calif.
Hughes Space and Communications Company, Los Angeles, Calif.
Innovative Concepts Inc., McLean, Va.
Innovative Solutions International, Vienna, Va.
Jet Propulsion Laboratory, Pasadena, Calif.
Lawrence Livermore National Laboratory, Livermore, Calif.
National Institute of Standards and Technology, Boulder, Colo.
Naval Research Laboratory, Washington, D.C.
Navward Systems, Dallas, Tex.
Odetics, Inc., Anaheim, Calif.
Pacific-Sierra Research Corporation, San Diego, Calif.
Raytheon Systems Company, Fullerton, Calif.
Science Applications International Corporation (SAIC), Torrance, Calif.
SFA, Inc., Washington, D.C.
Space and Naval Warfare Systems Center, San Diego, Calif.
Timing Solutions Corporation, Boulder, Colo.
TrueTime Inc., Santa Rosa, Calif.
TRW Space and Electronics Group, Redondo Beach, Calif.
U.S. Air Force, GPS Joint Program Office, Los Angeles Air Force Base, Calif.
U.S. Air Force, Schriever Air Force Base, Colo.
U.S. Naval Observatory, Alternate Master Clock, Schriever Air Force Base, Colo.
U.S. Naval Observatory, Washington, D.C.
U.S. Naval Sea System Command, Washington, D.C.
University of Colorado, Boulder, Colo.
University of Delaware, Newark
Welkin/CSC, Chantilly, Va.
Zeta Associates, Fairfax, Va.
Zyfer, Inc., Anaheim, Calif.

U.S. institutions. The U.S.-based contributions have gone from 61 percent of the total papers to 37 percent.

Changes in some specific categories are particularly revealing. The contributions from U.S. government laboratories and from U.S. industry in the acoustics area, though not large in 1991 and 1992, dropped significantly by 2001 and 2002. This is in stark comparison to non-U.S. contributions in the same area. U.S. government laboratory contributions in the nonacoustic areas have not changed much,

BOX 3.2
Foreign Participants at the 1999 and 2000 PTTI Symposia

Australia	CSIRO National Measurement Laboratory, Sydney
	National Measurement Laboratory
Austria	Space Research Institute, Graz
	Technical University of Graz
	Technische Univerität Wien, Vienna
Belgium	Royal Observatory of Belgium, Brussels
Canada	Marconi Canada, St-Laurent
	National Research Council, Ottawa
	NovAtel, Inc., Calgary
	University of Calgary
	Université de Montréal
China	Shaanxi Astronomical Observatory
Denmark	The FreeBSD Project, Slagelse
France	Bureau International des Poids et Mesures, Sèvres
	Centre National d'Etudes Spatiales, Toulouse
	CEPE, Argenteuil
	Observatoire de Besançon
Germany	DLR, Institut für Hochfrequenztechnik, Oberpfaffenhofen
	Physikalisch-Technische Bundesanstalt, Braunschweig
	TimeTech GmbH, Stuttgart
India	Accord Software and Systems Private Limited, Bangalore
Italy	Istituto Elettrotecnico Nazionale Galileo Ferraris, Turin
	Politecnico di Torino, Turin
Japan	Communications Research Laboratory
	National Research Center of Meteorology
	Tskuba Space Center, National Space Development Agency
Korea	Access Network Research Laboratory, Korea Telcom, Seoul
	Korea Telcom Research and Development Group, Seoul
Mexico	Guanajuato University, Salamanca
Netherlands	European Space Agency, ESTEC
Poland	Astrogeodynamical Observatory, Borowiec
Russia	Institute of Electronic Measurements KVARZ, Nizhny Novgorod
	Institute of Metrology for Time and Space, GP VNIFTRI, Mendeleevo
Singapore	Singapore Productivity and Standards Board
South Africa	National Metrology Laboratory, Pretoria
Spain	Real Istituto y Observatorio de la Armada, San Fernando
Switzerland	Astronomical Institute of the University of Bern
	Centre Suisse d'Electronique et de Microtechnique (CSEM) SA, Zurich
	Swiss Federal Office of Metrology, Wabern
	Temex Neuchâtel Time SA
Taiwan	Chunghwa Telecom
	National Taiwan University, Taipei
	Telecommunication Laboratories, Yang-Mei
Ukraine	Sichron Center, Kharkiv
United Kingdom	National Physical Laboratory, Teddington
	Quartzlock (UK) Ltd., Totnes

TABLE 3.6 Papers Published in *Proceedings of the IEEE International Frequency Control Symposium,* by Origin (United States versus non-United States)

	Total			United States			Other Countries		
Average of 1991/1992									
All papers	101			62 (61)			39 (39)		
Acoustics papers	56 (55)			29 (29)			27 (27)		
	Univ.	Lab.	Ind.	Univ.	Lab.	Ind.	Univ.	Lab.	Ind.
	15 (15)	21 (21)	20 (20)	7 (7)	10 (10)	12 (12)	8 (8)	11 (11)	8 (8)
Nonacoustics papers	45 (45)			33 (33)			12 (12)		
	Univ.	Lab.	Ind.	Univ.	Lab.	Ind.	Univ.	Lab.	Ind.
	7 (7)	24 (24)	14 (14)	3 (3)	18 (18)	12 (12)	3 (3)	6 (6)	3 (3)
Average of 2001/2002									
All papers	144			53 (37)			91 (63)		
Acoustics papers	95 (66)			28 (19)			67 (47)		
	Univ.	Lab.	Ind.	Univ.	Lab.	Ind.	Univ.	Lab.	Ind.
	47 (33)	18 (22)	30 (21)	14 (10)	5 (3)	9 (6)	32 (22)	13 (9)	22 (15)
Nonacoustics papers	49 (34)			25 (17)			24 (17)		
	Univ.	Lab.	Ind.	Univ.	Lab.	Ind.	Univ.	Lab.	Ind.
	15 (10)	29 (20)	5 (4)	3 (2)	19 (13)	3 (2)	12 (8)	10 (7)	2 (1)

NOTE: Univ., universities; Lab., government laboratories; Ind., industrial laboratories. Information estimated from the advance program for 2002. Numbers in parentheses are percentages.

but U.S. industry papers decreased dramatically. Also note the large number of papers from non-U.S. universities in 2001-2002. It should be pointed out, however, that most U.S. university work in atomic physics gets presented at physics conferences rather than at the IEEE-IFCS. The increase in U.S. university contributions in acoustics is largely attributable to sensor papers. Table 3.7 breaks down U.S. contributions and those of other countries at the IEEE-IFCS conference. The decrease in U.S. contributions is dramatic, and the 1999 conference—which was held in Europe in conjunction with the European Frequency and Time Forum—indicates the magnitude of foreign contributions.

The United States lags behind France, Japan, and other countries in supporting university research in PTTI applications. A single university in France, the Ecole Nationale Supérieure de Mécanique et des Microtechniques, in Besançon, has more researchers working on quartz crystal devices than the United States. (As part of its national effort aimed at making it the world leader in frequency control, France has made major investments in both university and industrial research.)

TABLE 3.7 Papers by Country of Origin for IEEE-IFCS Conferences in Selected Years

Conference Location	Year	United States	Germany	United Kingdom	France	China	Japan	Russia/ USSR	Other	Joint Foreign-Foreign	Joint U.S.-Foreign	Unidentified	Total Papers	Percent U.S. Authors
Atlantic City	1975	43			6		5					6	60	71.7
Philadelphia	1980	40	1		10		9		2			8	70	57.1
Philadelphia	1985	52	1	4	8	2	11	0	9	1	2		90	60
Baltimore	1990	52	1	3	5	0	8	0	7	1	3		80	68.8
Los Angeles	1991	57	1	0	4	0	11	7	8	1	3		92	65.2
Hershey, Pa.	1992	60	3	0	8	2	4	13	11	2	7		110	60.9
Salt Lake City	1993	54	1	1	10	4	6	16	12	2	7		113	54
Boston	1994	56	2	0	9	3	10	17	19	0	2		118	49.2
San Francisco	1995	59	0	2	10	2	12	20	12	2	2		121	50.4
Honolulu	1996	80	4	0	10	6	33	10	22	2	5		172	49.4
Orlando	1997	61	5	2	13	10	19	10	17	7	6		150	44.7
Pasadena	1998	72	5	4	9	2	20	11	11	8	9		151	53.6
Besançon	1999	57	14	9	48	9	29	25	61	24	15		291	24.7
Kansas City	2000	52	4	3	10	4	18	12	8	5	6		122	47.5
Seattle	2001	49	9	2	14	9	21	12	16	6	4		142	37.3

NOTE: In 1999, there was a joint meeting of the European Frequency and Time Forum and IFCS.

4

Research Opportunities in PTTI

In typical applications of PTTI, entire systems consisting of the high-performance clocks, local oscillators, and distribution systems provide the needed signal. For this reason, advancing the sciences of PTTI requires research in a variety of fields. Some of the research is already targeted for other applications, and PTTI is a beneficiary of the investments that are being made in them. One such field is high-performance, low-noise electronics, which is required for a variety of applications. Other fields of research are more specific to PTTI and must be supported directly, among them certain areas of AMO physics, materials science, and chemistry.

ATOMIC, MOLECULAR, AND OPTICAL PHYSICS

AMO physics is closely associated with PTTI technology. This area includes atomic physics, quantum metrology, and quantum optics. The most stable and accurate clocks are based on techniques and fundamentals derived from AMO physics. State-of-the-art atomic clocks based on the laser cooling of ions and the laser cooling and trapping of neutral atoms, have one to two orders of magnitude higher accuracy than conventional thermal beam or collisionally cooled atomic clocks. The trapping of atoms with magneto-optic traps (MOTs) or far detuned light fields to allow confinement of neutral atoms is essential for the isolation of atoms from the perturbing collisions that are encountered with cell confinement. This reduces Doppler broadening of atomic transitions by significant amounts, reducing first- and second-order Doppler shifts to nearly negligible values. Laser excitation of atoms is crucial to increasing the signal-to-noise ratio of the observed transition, a parameter that determines the ultimate stability of the clock. Advanced clocks operating with laser excitation are limited only by the fundamental quantum noise limit. AMO physics will undoubtedly continue to advance high-performance PTTI systems. The use of Bose-Einstein condensates (BECs) to realize high-performance clocks holds great promise. The very cold temperatures, the high coherence, and the very high phase space densities associated with BEC are precisely the parameters that relate to the performance of an atomic clock. Development of optical frequency combs that can be used to relate optical and microwave frequencies may enable application of laboratory devices based on optical transitions to possess up to three orders of magnitude

better accuracy than current microwave-based devices. Beyond this, research in quantum processes that allow clocks to operate below the fundamental quantum noise level promises the realization of even more performance. Theoretical studies addressing this issue have been pursued, and a potential experimental realization, so-called spin squeezing, has been demonstrated by researchers at NIST.

Device size and power consumption are as important to many PTTI applications as are stability and accuracy. Recent developments in AMO physics may also contribute here. The coherent population trapping (CPT) clock represents a new class of atomic clock having an inherent simplicity that renders it particularly suitable for applications where size and the power consumption bear a premium. While the feasibility of these clocks was first demonstrated in 1984, it is only within the past several years that operating clocks based on this approach have been built in the laboratory. This area of research is still quite young and will require much work before applications might be realized.

MATERIALS SCIENCE

Materials science plays a key and often underappreciated role in the development of PTTI devices.[1] Materials are crucial to the realization of high-performance clocks, since they help isolate the high-performance elements of the device from environmental effects, reduce the size and weight of devices, and enable operation in adverse environments such as space. Some research has been funded in piezoelectric materials for the development of resonators with performance superior to quartz. Support for this research has been dwindling. Opportunities in other areas of materials research have been overlooked. Below the committee identifies some areas of materials science research that could lead to improvement in PTTI devices and systems.

Processing and Packaging of High-Stability Resonators

Many of the designs and processes used in high stability resonators were invented more than 30 years ago. Promising new designs, processes borrowed from semiconductor microfabrication technology, and innovative packaging methods have been proposed but not implemented for lack of resources. Advances in these areas could lead to lower cost, more reliable, more compact packages for high-stability resonators.

Microresonators and Thin-Film Resonators

Microresonators and thin-film resonators promise to provide miniature (e.g., MMIC-compatible) and high-frequency (above 100 GHz) resonators, filters, and sensors. Both piezoelectric (quartz, aluminum nitride, zinc oxide, and other) and nonpiezoelectric (e.g., silicon) devices show great promise. Silicon microresonator arrays, although not temperature stable, show great promise for on-chip integration as (low-frequency) filters and sensors. Advances in this area have the potential to provide more compact radio frequency front ends (integrated circuit designs rather than discrete bulk devices) by reducing the size of the pre-down-conversion filters and duplexers in receivers and transceivers.

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[1]Some text in this section, on materials science, and the next, on chemistry, was extracted from Office of the Under Secretary of Defense, Acquisition and Technology, *Special Technology Area Review (STAR) on Frequency Control Devices*, U.S. Department of Defense, Washington, D.C., 1996.

Microstructured Optical Fiber

Heterodyned optical atomic clocks have been achieved by the development of microstructured optical fiber combined with advanced mode-locked lasers. Further research to improve the reproducibility of fiber performance and to extend these fibers to infrared wavelengths would improve optical atomic clocks and many other technologies. Currently, there are only a few sources of microstructured fiber, and none are specifically targeting PTTI research.

Low-Power, High-Accuracy Quartz Clocks

The feasibility of achieving a 100-fold improvement in stability with the microcomputer-compensated crystal oscillator (MCXO) has been shown. However, to achieve such performance reproducibly and to extend the performance, the frequency versus temperature hysteresis problem for such crystals must first be solved. The noise, power, and size of the MCXO also need to be reduced. These problems have not been solved because the resources directed toward crystal research were inadequate. Improvements in crystal oscillators can decrease the vulnerability of frequency-hopping systems to smart jammers and improve the ability to locate radio emitters in the field.

Low-Noise Resonators and Oscillators

Several technologies for low-noise oscillators need to be explored. These include (1) surface transverse-wave resonators and dielectric resonator oscillators for ultralow noise floors and (2) novel bulk acoustic wave (BAW) and surface acoustic wave (SAW) resonators for vibration-insensitive oscillators. Fundamental noise studies in piezoelectric devices (for example, of $1/f$ noise) are also needed. The availability of low-noise resonators and oscillators has the potential to improve missile accuracy and improve surveillance systems, provide more accurate onboard radar systems for missile guidance, improve IFF systems, and enable more effective radar spoofing.

CHEMISTRY

Many key performance parameters of clocks and oscillators are directly impacted by processes related to chemistry. Below, some aspects of chemistry that can potentially lead to higher-performance atomic clocks and local oscillators are identified.

Solid-State Chemistry

Solid-state chemistry research could further the availability of high-perfection quartz. Evidence indicates that the stability of quartz devices is limited by quartz imperfections, such as dislocations and impurities. The feasibility of growing dislocation-free, ultrahigh-purity quartz has been demonstrated in the United Kingdom, but there is still no method for producing amounts sufficient to meet DOD needs. Developing such a capability could pay off by enabling the production and fielding of low-power, low-cost, high-performance quartz clocks that would make frequency-hopping systems virtually invulnerable to smart jammers and improve the ability to locate radio emitters.

Quartz has been used exclusively in high-stability oscillators but has serious limitations, such as a phase transition at 573°C that prevents the use of high-temperature manufacturing processes for purification and stress relief. During the past decade, new piezoelectric materials were discovered that show

great promise for providing the advantages of quartz without its limitations and giving better performance. Langasite, a lanthanum gallium silicate ($La_3Ga_5SiO_{14}$) invented in Russia, and lithium tetraborate, invented in the United Kingdom, are examples. These materials have a lower acoustic attenuation and higher piezoelectric coupling. Programs to further develop, characterize (with respect, for example, to linear and nonlinear material constants as functions of angles of cut and temperature), and establish U.S. sources for these and other (e.g., gallium phosphate) materials are needed. New optical materials could also eventually find use as local oscillators. Materials with large electro-optic coefficients, such as ferroelectrics, are used for OEOs. Research is needed to evaluate known materials, with the eventual goal of optimizing material characteristics. For example, ferroelectrics demonstrate piezoelectricity that deleteriously affects vibration sensitivity. Successful demonstration of such new materials could lead to high spectral purity at frequencies above 10 GHz.

Surface Chemistry

Isolation of atoms in atomic clocks is required to obtain the most precise signals. Wall coatings are used to reduce spin relaxation during wall collisions. The wall coatings currently used in hydrogen masers cannot be used for alkali metal (rubidium, cesium)-based atomic clocks owing to long-range electron-transfer (harpooning mechanism) reactions between the alkali atoms and fluorine-containing wall coatings. Even the coatings currently used in hydrogen masers have not been optimized. A research program in self-assembled monolayers (SAMs), for example, would be extremely useful for investigating ways of reducing container wall collision interactions. Reducing collisions could lead to smaller device cavities, higher-performance hydrogen masers, and higher-performance alkali-metal-based clocks and contribute to the realization of a chip-scale atomic clock.

OTHER AREAS

Resonator Theory, Modeling, and Computer-Aided Design of Resonators and Oscillators

The theory of resonators is highly complex. Finite element model (FEM) calculations of "real" three-dimensional resonators have not been feasible until recently owing to the inordinately long supercomputer calculation times required. With improved supercomputers and algorithms, computer-aided design (CAD) of resonators and oscillators is becoming feasible. Atomistic models are also becoming feasible with the aid of powerful computers. Research programs at universities are needed to realize the required CAD models and simulation capabilities. Improvements in resonator design can lead to devices for improved missile accuracy, better surveillance systems, more accurate onboard radar systems for missile guidance, superior IFF systems, and the ability to effectively conduct radar spoofing.

Micro- and Nanoscale Sciences

High-performance atomic clocks could greatly benefit from new approaches for confining atoms and for exciting atomic transitions. Nanosciences are poised to play an important role in reducing the size and power consumption of these devices. MEMS technology already has produced high quality-factor resonators that promise to enable local oscillator operation near the performance level of quartz at a fraction of size, weight, and power consumption.

While the significantly narrow transitions associated with electromagnetically induced transparency in condensed matter systems are currently possible only with cryocooled samples, it is not unreasonable

to expect that technologies related to caged atoms and clathrates may play a significant role in future high-performance clocks, especially with respect to size and robustness. Techniques of the nanosciences may also become invaluable in devising approaches that allow direct detection of the polarization state of an atom.

Micro- and nanoscale technology also promise to aid the development of a chip-scale atomic clock. If realized, this could profoundly impact the tactical use of the GPS in adverse and jamming environments.

Photonics Technology

Many realizations of the laser-cooled or laser-excited atomic clocks rely on low-cost and low-power semiconductor lasers. These devices are needed at specific wavelengths corresponding to cesium and rubidium transitions. Issues related to the fabrication, ruggedization, and radiation hardening of semiconductor devices at these specific wavelengths remain for researchers to pursue. Research in other devices, including high-efficiency modulators and switches, passive optical elements, and optical whispering-gallery-mode microresonators also could greatly benefit high-performance PTTI. Such research could advance atomic clocks and local oscillators, including those currently based on the photonics technology, such as the OEO.

5

Defense Needs for PTTI

Over the last two decades, U.S. warfighting capabilities have undergone a revolution enabled by a number of essential technologies. For example, advances in microelectronics have been applied to communications, signal processing, and computational power. Electro-optics technology has found application in sensors for detectors and imaging, laser range finders, target designators, inertial navigation systems, and communications. A less obvious but equally essential technology is PTTI. One need only consider the precision targeting resulting from GPS, enabled by PTTI, to appreciate its role. Much of the success of the U.S. armed forces in the last 15 years has depended on the synchronization and dissemination of precise time. The Navy, through NRL and USNO, has been the major force within DOD in turning laboratory demonstrations into operationally useful PTTI devices. Like many technologies, much of PTTI's usefulness was foreseen only dimly, if at all.

THE ROLE OF PTTI IN MILITARY OPERATIONS

There are many particular examples of essential military operations that depend on PTTI and would benefit from improvements in clock technology. The committee again emphasizes that such improvements go beyond drift rate to considerations such as power, ruggedness, size, and other similar factors. The following areas are offered as a representative sample, with speculation on how improvements in PTTI would impact each.

GPS Clocks and Autonomous Operation

Atomic clocks are flown on GPS satellites to maintain the phase accuracy of the transmitted GPS signal, which ensures an accurate one-way range measurement for the user. These clocks also serve as flywheels to maintain the synchronization of the GPS system if uploads of time signals from the GPS ground station to the satellite constellation are temporarily unavailable.

Recent improvements to GPS atomic clocks demonstrate the power of PTTI for the warfighter. Rubidium clocks flown on GPS Block IIR have much better stability than those flown on GPS

Block II/IIA. The ranging error with the improved clocks is almost halved. These ranging accuracy improvements allow a proportional improvement in positioning and time outputs from a GPS receiver.

Further improvements in stability and ruggedness of the atomic clocks flown on GPS satellites could do the following:

- Improve the ranging accuracy, reducing collateral damage, enabling more accurate weapons delivery, and subsequently reducing the number of missions required to destroy a target set.
- Allow longer GPS operations in the event of a ground upload outage.
- Enhance clock lifetime, lowering the clock failure rate and reducing the cost of sustaining the GPS satellite system.

Weapon System Four-Dimensional Coordination

Naval operations are unique in their distributed nature, so four-dimensional coordination of weapons systems is of particular importance to the Navy. For example, missile defense systems typically use radar to locate incoming missiles and predict their flight paths. This four-dimensional location must then be sent to an interceptor that is using the same four-dimensional coordinate system. It is clear that the four-dimensional coordination requirements to achieve success in such a system are formidable. Through GPS, PTTI plays a central role in four-dimensional coordination, helping to define the spatial coordinate frame and coordinating the time dimension. As warning times decrease, the demands on the system and PTTI will become greater, placing greater demands on four-dimensional coordination. There are similar examples in antisubmarine warfare and the attack of fleeting targets.

Advances in PTTI such as more accurate time dissemination and synchronization would provide better overall time coordination between distributed assets. For the warfighter, this could mean

- More accurate targeting, particularly for time-of-arrival location systems,
- Faster reaction times, and
- Increased probability of kill, with subsequent reduction in sorties or rounds fired.

GPS Antijamming and the Two-Satellite Solution

If enemy jamming is present, direct acquisition of GPS signal is necessary. Direct acquisition requires a search for the start of the code signal. If the user has accurate knowledge of time from his local clock, the time required for this search can be reduced. This can be critical in battle situations—for example, in a guided weapon that may have less than a minute to lock up, as in the current weapon system design for a joint direct-attack munition (JDAM). To maintain 100-microsecond acquisition time uncertainty over 12 hours requires a clock with stability of 2×10^{-9}. Current receiver clocks, with typical stability of 1×10^{-6}, drift this far in 100 seconds. While other solutions to this problem are possible, clocks better in all aspects would allow trade-offs when the system is being designed.

In other situations—for example, under jungle canopies or in urban canyons and mountainous terrain or in case of satellite failure—fewer than the normal four GPS satellites are in view. If the user has accurate time from his local clock and independent knowledge of altitude, a position fix can be obtained with only two satellites. Ranging accuracy goes approximately as (drift rate × time since update). If the last time update was 2 hours earlier and the equivalent ranging accuracy requirement was 200 meters, drift rates of less than about 10^{-10} would be required in a low-power, rugged, lightweight device. A solution to the two-satellite problem would be particularly useful to Marines and Army personnel.

Both GPS antijamming and the two-satellite problem could be addressed by better local clocks. Decreasing the size, weight, power requirements, and cost of devices to achieve higher-accuracy handheld clocks could affordably accomplish two things:

- Enable navigation and positioning under impaired GPS conditions.
- Enable weapons release under hostile jamming.

Network-centric Warfare

Internetted warfare (or, in Navy terms, network-centric operations) are military operations that exploit state-of-the-art information and networking technology to integrate widely dispersed human decision makers, situational and targeting sensors, and forces and weapons into a highly adaptive, comprehensive system to achieve unprecedented mission effectiveness.[1] It involves the concept of electronically connecting all of the platforms in an area of operations, so that all assets can communicate digitally with all others in the area and even with out-of-area assets. Instead of individual platforms (ships, aircraft, etc.) being the centerpiece of Navy forces, each platform would be a node within a large architecture. These nodes, if effectively connected, could bring their warfighting assets or warfighting support to bear in a very short period of time, thus enhancing the warfighting capability of the naval force. Network-centric warfare seeks to allow naval forces such as ships, aircraft, ground stations, and satellites to communicate effectively with each other so that Navy forces can do the following:

- Reach decisions and commence operations faster than an adversary.
- Self-synchronize, that is, all layers of command and forces can know enough about the tactical and strategic situation to anticipate the next command and be ready when the command actually comes.

Network-centric warfare is more than classical communications. It includes systems such as the Navy's cooperative engagement capability (CEC). CEC enables battle-group ships and aircraft to integrate sensor and weapons system data into a single integrated architecture. With CEC, any ship can shoot at an enemy aircraft based on tactical displays developed on other ships. The CEC system depends, among other things, on the speed of communications that link the computers together and the accuracy of the grid systems for tracking Navy ships and enemy aircraft.

Basically, anything that makes communications faster and more effective will contribute to network-centric warfare. Multiple communications circuits will need reliability, security, and speed of synchronizing. An accurate grid system for tracking the positions of both friendly forces and adversaries is also essential to this network approach to warfighting. All these things are dependent upon PTTI and can be improved by PTTI advances. Improving the accuracy, precision, and stability of shipboard timing by reducing the cost and size of high-performance clocks and improving their ruggedness would, in turn, improve the following:

- Speed of communications processing, allowing friendly assets to be brought into play quicker than the adversary's assets,
- Accuracy of location grid, allowing better control and identification of friendly and adversary platforms, and

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[1]See Naval Studies Board, National Research Council, *Network-Centric Naval Forces: A Transition Strategy for Enhancing Operational Capabilities*, National Academy Press, Washington, D.C., 2000.

• More accurate adversary track data generated by and processed or communicated between multiple ships in a CEC.

Secure Military Communications

Military operations place stricter demands upon communication systems than civilian uses. Higher rates of data transmission are required, while maintaining high-quality service (low error rate and high reliability). Transmissions must be robust in the presence of jamming and secure, with a low probability of interception. Spread-spectrum approaches are typically used for secure communications. (Some commercial communications systems also rely on spread spectrum.) Several techniques are used to spread the bandwidth, including patterns of phase modulation and hopping among a set of frequencies. Typically, the specific patterns of the signal are defined by pseudo-random codes. In an attempt to provide improved security, encrypted codes are being employed that require an acquisition sequence similar to GPS. Accurate knowledge of time can speed up or enable acquisition.

Spread-spectrum and frequency-hopping techniques are central to communication systems such as Link-16, strategic applications of the MILSTAR satellite communications system, and the Navy's Situational Beacon and Reply (SABER) system for battlefield and battle-group situational awareness. Time synchronization and precise frequency control are of fundamental importance to system function for all of these techniques. Further challenges arise from the necessity to maintain such systems in demanding tactical environments ranging from combatants on the ground to aircraft in stressed dynamical conditions. Precise, independent knowledge of time reduces user dependence on extracting time from transmitted signals. This is directly related to time required to acquire a spread-spectrum signal so that the user can begin communicating.

Improvements in PTTI technologies, particularly those that realize high performance in small packages, would enable two things:

- Rapid signal acquisition, particularly in a jamming environment, and
- Greater data capacity through closer channel spacing and more precise time slot allocation.

NAVY PTTI REQUIREMENTS

Figure 5.1 summarizes the current unclassified formal Navy requirements for PTTI, as determined from a list compiled by N70T. These requirements fall along a spectrum of required accuracy and come from a wide variety of the Navy's programs; a notable number are high-accuracy requirements. As military utility has become more apparent, these requirements tend to become more stringent in all aspects (not just frequency and time stability). PTTI has been, is, and will continue to be a critical enabler in warfare. Advances in this technology will surely lead to more effective and productive armed forces.

New Paradigms for the Navy and DOD

The committee can envision relatively new and increasingly important drivers for PTTI advances, based on the changing nature of conflicts, including the following:

- The need for all-weather precision weapon delivery and target location,
- Low political tolerance for collateral damage,

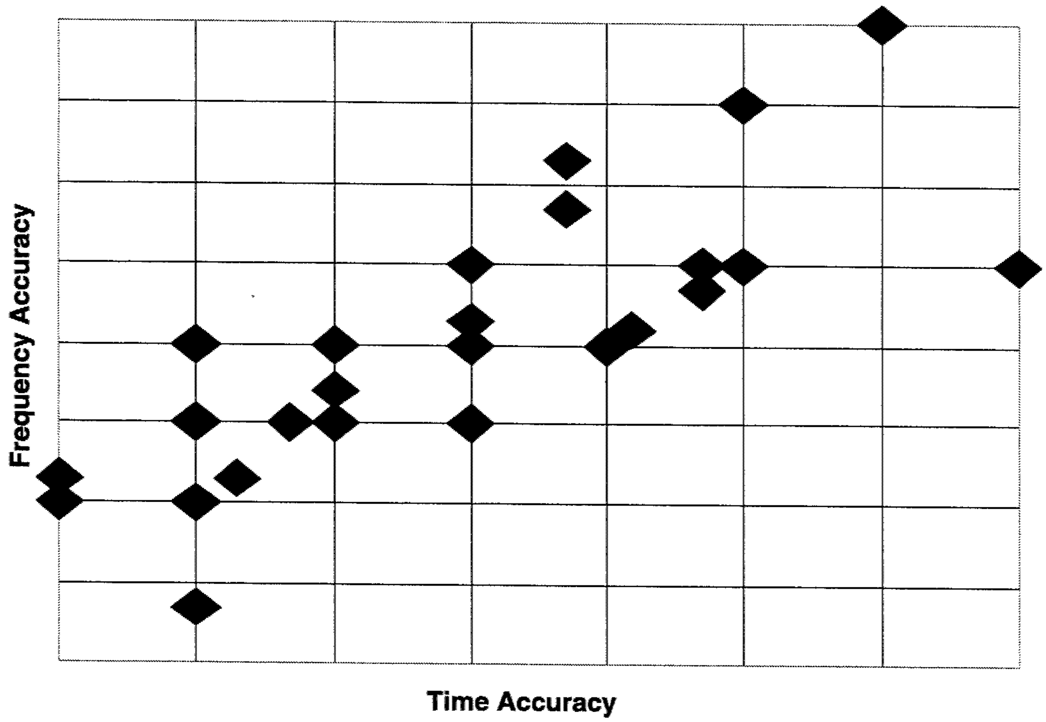

FIGURE 5.1 Current formal Navy requirements for PTTI, as compiled for the committee by N70T. Not included are the classified programs, some of which presumably are pushing the state of the art in PTTI. Forty-three programs are shown (some points overlap).

- The needs of homeland defense, including information security, locating homeland jammers, and tagging and tracking terrorists,
- The reduction in overseas bases and subsequent increased reliance on long-range support, and
- The increased need for data fusion and time correlation of events to allow a glut of data to be transformed into useful information.

6

Findings and Recommendations

NEED FOR PTTI

Finding: Accurate time and frequency have been, are, and will be critical to the Navy's (and indeed all of DOD's) war-fighting capability.

The original driver for significant improvement in knowledge of time was the need to determine longitude in navigation of the seas, which led to the development of the chronometer. Today, PTTI technology has proven to be of enormous leverage in war fighting. Comparison of signals between ground- and space-based clocks is the foundation for GPS and its myriad applications to precision force location and operations and to precision-guided munitions. Today, precise time synchronization is needed to determine efficiently the start of a code sequence in secure communications and the precise location of emitting targets, and precise frequency control is required for spectrum utilization and for frequency-hopped, spread-spectrum communications. The recent upgrade of the rubidium standards flown on GPS satellites has decreased the user equivalent range error achieved with GPS by a factor of one-half, which can improve the probability of kill and reduce the number of sorties, casualties, and unwanted collateral damage.

Advances in PTTI, including a reduction in size, weight, and power required for mobile devices, an improvement in the ruggedness of field systems, and more precise and accurate time dissemination, will lead to improvements in DOD capabilities that rely on PTTI. For example, rugged chip-scale atomic clocks with 10^{-11} accuracy would significantly improve networking and weapons system effectiveness by enabling better four-dimensional coordination of systems. Reliable oscillators would improve the jamming resistance of GPS-guided munitions by enabling faster direct acquisition of the GPS signal in cases of jamming. Increased speed of disseminating command knowledge on the battlefield, combined with smaller, more precise weapons, would reduce collateral damage and, in turn, operational and political costs. In addition to improving existing systems, the historical record strongly suggests that further advances in PTTI technology will enable advances in systems autonomy and weapons accuracy, leading to new war-fighting capabilities that are only dimly foreseen today.

PTTI INFRASTRUCTURE

Finding: Internationally, the United States is an important player in PTTI research but no longer the dominant one.

Increased foreign participation in major PTTI conferences attests to the fact that the United States has more competition in PTTI research than was true historically. Countries such as Australia, China, Finland, France, Germany, and Russia all train students specifically in PTTI technology.

Recommendation: While it is important to retain U.S. leadership in PTTI, ONR and USNO should consider whether opportunities exist to take advantage of growing foreign competence in PTTI by cooperating with allies. This might defray the cost of some current programs, freeing resources to pursue advances in other areas of PTTI.

Finding: Training in precision frequency control and timing per se is rare in the United States, and training in the fields relevant to PTTI is mixed—some is adequate, some is not.

U.S. researchers in atomic frequency standards and clocks are generally drawn from the ranks of students trained in atomic physics and precision measurements. Years of on-the-job training then turn these researchers into PTTI experts. A number of U.S. universities provide training in atomic physics and precision measurements relevant to PTTI, and a number of federal laboratories support training opportunities that focus on development of advanced atomic clocks and frequency standards.

In particular, however, there is a dearth of U.S. training opportunities in areas relevant to high-precision quartz resonators and oscillators, which play a key role in most applications that utilize PTTI in the field. There are a number of areas for potential improvements in the performance of these oscillators that would translate directly into improved systems for the warrior. Without trained researchers in this area, the United States risks losing out on such improved systems.

Finding: There is little incentive for commercial firms to produce PTTI devices for defense systems.

A large market exists for inexpensive quartz crystal oscillators for applications such as watches, cell phones, and other relatively low-precision consumer goods. The market for defense-quality quartz oscillators is miniscule in comparison with this lower-quality market. The situation is similar for atomic clocks, where the largest market for moderate-quality clocks is commercial telecommunications. Relative to this market, the purchase of high-precision clocks for defense systems is infrequent and involves a small number of clocks.

Most defense applications also require oscillators and clocks that can withstand the harsh operating environments of the battlefield and space. Such environmental factors pose severe engineering challenges for device designers. Products for the consumer market or for the telecommunications industry are not made to operate in these environments, so commercial firms that manufacture for civilian applications cannot readily shift into production of devices for defense purposes.

Industry needs a steady source of funding in order to maintain precision frequency sources for special applications, such as space-qualified, severe environments and very small size and power requirements. In particular, without sustained support, precision quartz oscillators may no longer be available from U.S. sources.

PTTI AS A NATIONAL NAVAL RESPONSIBILITY

Finding: Past Navy funding for basic research in atomic and molecular physics has led to significant advances in PTTI.

For example, ONR was a supporter of the research that led to three Nobel Prizes in physics—Norman Ramsey in 1989, Bill Phillips in 1997, and Carl Wieman, Eric Cornell, and Wolfgang Ketterle in 2001. ONR-funded spectroscopic studies by Ramsey (Harvard University) in the 1940s led to the design of the microwave interrogation method that remains an essential part of high-accuracy clocks today. ONR was an important early funder of work in the 1980s by Phillips (NIST) in laser cooling and trapping of atoms, a technique that is at the heart of today's most accurate clock, the cesium fountain clock. ONR was also an important early funder of work by Cornell, Wieman (JILA), and Ketterle (Massachusetts Institute of Technology) in the 1990s that led to the realization of the Bose-Einstein condensate, a form of ultracold matter that had been predicted theoretically some 70 years earlier but never realized. This breakthrough has not yet been applied to PTTI, but just as PTTI built on the scientific groundwork laid by Ramsey and Phillips to further advance basic physics, Cornell, Wieman, and Ketterle's work is also expected to lead to PTTI applications. These investigators all had as their primary goal advancing our fundamental scientific understanding of nuclei, atoms, and molecules, and the judicious support of their research ideas by ONR program officers led to fundamental advances in PTTI as well.

Finding: The U.S. Navy has been the principal developer of advanced atomic PTTI technologies for DOD applications.

ONR funding was key to the development and commercialization of cesium atomic beam clocks, rubidium gas cell clocks, and the hydrogen maser. These three technologies, together with precision crystals (supported mainly by the U.S. Army), account for all commercially available precision clock technology. The NRL Timation project and subsequent Navy developments in satellite navigation and orbiting precision clocks led to today's GPS and resulted in NRL funding being DOD's main source for the development of advanced atomic clocks for space. USNO has been a key player in the development of precise time coordination and transfer techniques such as GPS common view, GPS carrier phase, and two-way satellite time transfer.

Finding: PTTI is a Critical National Defense Technology, and advances in PTTI that are most relevant to defense will only be developed under military sponsorship. PTTI is of benefit to all the Services and is essential to the Navy.

DOD has unique needs in the area of PTTI. These include applications operating under environmental extremes, with low power consumption and light, compact design, and autonomous submarine operation over long periods. PTTI technologies enable

- Rapid direct Y-code acquisition of GPS and coded communications,
- Precise positioning and maneuver of assets,
- GPS-guided munitions,
- Network-centric warfare capability using high-speed, broadband data transmission to war-fighting units, and
- Greater precision low-cost weapons with improved antijam capabilities.

Finding: Only the Navy possesses the technical capabilities and sustained interest in PTTI that will meet DOD needs for operational atomic clocks.

The Navy has historically played a large role in PTTI. The depth and scope of its S&T budget for PTTI research over the past 30 years exceed the depth and scope of the U.S. Army and Air Force investments. USNO is the designated agency for providing a real-time estimate of Coordinated Universal Time (UTC). Additionally, DOD directive 5160.51 recognizes the Navy as the PTTI manager. The Navy has served as a resource for others in the DOD requiring PTTI. Traditionally, the ONR has taken the lead in supporting research and development in PTTI because of its critical importance for navigation.

While other services do fund PTTI-related research and development, there are certain aspects of PTTI that depend directly on Navy capabilities and investments. These include but are not limited to

- Maintenance of state-of-the-art atomic clock stability in space military environments,
- Maintenance of a fundamental time reference with at least an order of magnitude better timing accuracy than that used by any DOD application, and
- Global dissemination of precise timing signals for military use.

Recommendation: Based on the above considerations, the committee recommends that PTTI should be established as a National Naval Responsibility.

OPPORTUNITIES TO ADVANCE PTTI SCIENCE AND TECHNOLOGY

Finding: Significant opportunities to advance PTTI science and technology do exist and can be pursued if resources are directed at them.

Pursuit of advanced concepts such as those utilizing optical frequencies should advance the precision available today in laboratory clocks by one or more orders of magnitude. Local oscillator improvements can be obtained by better understanding of quartz crystal systems and by pursuit of optoelectronic oscillators. Materials development can better isolate sensitive clock elements from noise and decrease the size and weight of devices, enabling higher-precision PTTI applications on the battlefield. MEMS, nanoscale devices, and coherent population trapping may also play a role in enabling smaller, lighter devices with greater precision than is currently available on the battlefield.

Finding: Some areas of science and technology important to DOD PTTI applications are currently given insufficient attention, such as research to improve synchronization, local oscillators, and the ruggedness of small, low-power clocks.

Researchers have achieved orders of magnitude improvement in the accuracy of laboratory time measurements in the last two decades. We are not yet able to utilize this accuracy in fieldable systems, partly because not enough research has been devoted to areas critical to development of operational devices and partly because research, especially applied research, has not been effectively transitioned into fieldable capabilities.

Finding: Continuity of programs is required to ensure that expertise is transferred from one generation of PTTI researchers to the next.

The technology underlying PTTI is reliant on a level of precision not found in most other technologies. It places requirements on practitioners that cannot be learned without several years of training. To successfully build PTTI systems requires an understanding not just of the fundamental physics involved in high-precision frequency or time measurements, but also of all of the engineering factors that go into building a system that delivers that high precision in the real world. No course of academic training can produce an accomplished PTTI scientist; rather, an apprenticeship of sorts is required, in which the early career researcher works side by side with the accomplished PTTI scientist to learn the nuances of producing real systems of such incredibly high precision. For this reason, PTTI expertise, if lost, could not be readily rebuilt and certainly could not be rebuilt in a short (5 years) time.

Recommendation: ONR should stabilize its 6.1 funding of PTTI-related research at its current level or higher. Means should be sought to broaden basic research beyond atomic, molecular, and optical physics so that it includes enabling advances in materials science, chemistry, photonics, and other relevant areas. Support for quartz crystal research is of particular importance.

Recommendation: To improve the insertion of PTTI advances into DOD capabilities, ONR should increase 6.2/6.3 funding in PTTI, focusing on improvements in ruggedness; decreasing the size, weight, and power consumption of PTTI devices; and developing new and improved techniques for precise time dissemination and coordination.

Finding: Coordination and planning of PTTI activities between the Services, with DARPA, and between DOD and other agencies is fragmented. Both internal and external guidance are needed.

PTTI is important to all four branches of the military. Each has slightly different needs in PTTI, and three of the four branches, as well as DARPA, support their own program in PTTI research and development. However, the Department of the Navy's program supports more fundamental research than do those of the other Services. Based on the committee's data gathering and on its members' experiences, there seems to be little coordination of PTTI research and development activities between the Services. Of particular concern is an apparent lack of the planning required to leverage advances at both the basic and applied level and translate them into better military system performance. Coordination between the Services and with DARPA would result in a quicker and more complete capture of the benefits that come from PTTI advances. Similarly, coordination between DOD and other federal agencies with significant interest in PTTI technologies, such as NASA and NIST, could be strengthened.

The Department of the Navy, as the DOD PTTI manager, is responsible for coordinating the development of PTTI techniques among DOD components. As already noted, the committee finds that such coordination is lacking. This may be due in part to the difficulty of one Service (Department of the Navy) understanding and addressing the needs of the others. Not only is PTTI broader than the Department of the Navy, it is also broader than any one Department of the Navy or DOD program. For example, in the technology area review and assessment (TARA) process overseen by the DOD Director of Defense Research and Engineering (DDR&E), different aspects of PTTI research fall under different TARAs. Within ONR, PTTI-related 6.1, 6.2, and 6.3 research and development are found in several different program codes. They are also found within NRL. The committee could find no instance in which the PTTI program as a whole is regularly reviewed and no instances of external review. The committee is aware that the DOD PTTI manager convenes an annual review of advances in PTTI science; while this is useful, it does not replace review of the DOD strategy in PTTI. The committee has

already noted research areas that promise advances in PTTI and its applications that are not currently receiving significant attention from the Department of the Navy or DOD. The committee believes that regular advice from external technical experts could help the Department of the Navy construct its investment strategy and address these problems of breadth and coordination as it carries out its responsibilities as PTTI manager.

Recommendation: DDR&E should coordinate PTTI research DOD-wide and develop an insertion plan to ensure that 6.2/6.3 advances in PTTI are transitioned into operational military systems. To help DDR&E and to ensure that the Navy's responsibilities as PTTI manager are met, the Department of the Navy should convene regularly (at least annually) an outside, independent group of experts to address DOD needs in PTTI and opportunities in PTTI research.

Appendixes

A

Committee Biographies

David H. Auston, a member of both the NAS and the NAE, is president of the Kavli Foundation and Institute and a former president of Case Western Reserve University. Prior to his service at CWRU he held faculty positions in the departments of physics, electrical engineering, and computer science at Columbia University and Rice University, serving as provost at Rice. Before his academic career he established his reputation as a researcher at Bell Laboratories. His research expertise is in the areas of lasers, nonlinear optics, and solid-state materials. He is a recipient of the R.W. Wood prize of the Optical Society of America and the Quantum Electronics and Morris E. Leeds Awards of the Institute of Electrical and Electronics Engineers (IEEE). Dr. Auston's previous NRC service includes membership on the Committee on Criteria for Federal Support of Research and Development, the Board on Physics and Astronomy, and the Board on Assessment of NIST Programs and its panel for the Physics Laboratory, which he chaired for 2 years.

Leonard S. Cutler is a Distinguished Contributor of the Technical Staff, Agilent Technologies. He is a member of the NAE. Dr. Cutler is well recognized for his contributions to atomic frequency standards and atomic timekeeping and is a leader in the commercial development of atomic clocks. He has worked on diverse timekeeping systems, including cesium beam, rubidium, and mercury ion standards and precision quartz oscillators, and is sometimes referred to (by others) as "the father of the atomic clock" and "the time lord." He also works on remote synchronization techniques. He is a fellow of the IEEE and the American Physical Society (APS) and has received the IEEE's Morris E. Leeds, Centennial, and Rabi awards and shared the American Institute of Physics Prize for Industrial Application of Physics.

Robert E. Drullinger is a staff scientist at the National Institute of Standards and Technology in its Time and Frequency Division in Boulder, Colorado. He held various positions at NIST starting in 1972. His research has focused on advanced atomic clock concepts. He led the development of NIST-7, the world's most accurate atomic beam clock, and participated in the first-ever photon-pressure cooling of atoms and the first direct frequency measurement of visible light. He is part of a group of researchers who have demonstrated the world's first all-optical clock and is currently working to establish new

performance standards for the short-term stability and accuracy of that frequency standard. Dr. Drullinger wass the 1996 recipient of the IEEE Rabi Award.

Robert P. Frueholz is currently principal director, Communication Systems Subdivision, The Aerospace Corporation. He has held various positions at Aerospace, but since 1984 has maintained almost continually some responsibility in the areas of precision timekeeping and atomic frequency standards and their application to operational satellite systems such as GPS and MILSTAR. He has also worked in laser design and fabrication, the application of lasers to remote sensing, and microelectronics. In his current position, he is responsible for communications systems, from hardware—radio frequency and optical—through architectural studies.

Gerald Gabrielse is a professor of physics at Harvard University and is chair of the Physics Department. He leads the ATRAP Collaboration, an international research collaboration with the goal of accurate laser spectroscopy with trapped antihydrogen atoms. His research group is involved in a variety of atomic, optical, elementary particle, plasma, and low-temperature physics experiments. He is a fellow of the APS and is the winner of the Davisson-Germer Award for 2002. He participated on the NRC's Committee on High-Energy-Density Plasma Physics Assessment.

William P. Kelleher is group leader of the Electro-Optic Sensors Group at the Charles Stark Draper Laboratory. His responsibilities focus on research in optical sensors for inertial navigation, chemical sensing, and communications applications such as dense WDM and switching. He oversees R&D efforts in high-Q optical resonators, photonic bandgap sensors, and precision wavelength references for broadband light sources.

Glen Kowach received his Ph.D. in chemistry in 1995 from Cornell University under the guidance of Francis J. DiSalvo. After leaving Cornell, he joined the staff of Bell Laboratories/Lucent Technologies, where he was named a Distinguished Member of the technical staff after only 4 years. He was part of the team that discovered the first materials with negative thermal expansion. He has great breadth of knowledge about materials, with crystals and crystallinity being a particular interest. He was with Agere Systems during the course of this study but has since returned to Bell Labs.

Lute Maleki is a senior research scientist and technical group supervisor of the Quantum Sciences and Technology Group at the Jet Propulsion Laboratory. He has been involved in directing and conducting research in a number of areas related to the generation, distribution, and measurement of ultrastable reference frequencies. His current research focuses on the development of atomic clocks based on ion traps and laser-cooled trapped atoms; development of sensors based on atom wave interferometers; study and development of ultrastable photonic oscillators and signal distribution systems; study and development of whispering-gallery-mode microresonators; and tests of fundamental physics with clocks. Dr. Maleki is a fellow of IEEE and a winner of its Rabi Award.

Thomas E. Parker is a staff member in the Time and Frequency Division of NIST in Boulder, Colorado. He is the leader of that division's Atomic Frequency Standards Group. His interests include primary frequency standards, time scales, and time transfer technology. He played a large role in incorporating hydrogen masers into the NIST time scale, in improving the Two-Way Satellite Time and Frequency Transfer system, and in making frequency comparisons between primary frequency standards. Before joining NIST in 1994, Dr. Parker worked at Raytheon, where he contributed to the development of high-performance surface acoustic wave technology. He is a fellow of the IEEE.

Bradford W. Parkinson is Edward C. Wells Professor of Aeronautics and Astronautics at Stanford University. He is a member of the NAE. He is currently coprincipal investigator of the Gravity Probe B experiment and also maintains a research laboratory active in the research and development of applications of differential GPS. During his Air Force service he was the first program director for NAVSTAR/GPS. He has held positions at Rockwell International and Colorado State University and served as chair

of the NASA Advisory Committee and commissioner of the Presidential Commission on Air Safety and Security. He is a fellow of the Royal Institute of Navigation and the American Institute of Astronautics and Aeronautics.

Richard A. Riddell is a retired rear admiral, U.S. Navy, and is currently affiliated with General Dynamics. He held numerous positions of responsibility during his Navy career, culminating in directorships of the Special Programs Division and the Test and Evaluation and Technology Requirements Office of the CNO. He also served as director of the Strategic Submarine Division. As such, Admiral Riddell knows about naval needs in communications technology and applications of PTTI to communications and navigation. Admiral Riddell's awards include the Legion of Merit with four Gold Stars, the Meritorious Service Medal with two Gold Stars, and the Navy Commendation Medal with three Gold Stars. He is a graduate of the U.S. Naval Academy.

Samuel R. Stein is a founder and president of Timing Solutions Corporation, a company that specializes in real-time applications and provides timing systems to the national laboratories, DOD systems such as GPS, and government prime contractors. He has developed ultra-high-precision time measurement, generation, and distribution systems and is an internationally recognized leader in time and frequency measurement methods and the ensembling of clocks. He previously held management positions at Ball Corporation (Efratom Division) and the National Bureau of Standards (now NIST).

Robert F.C. Vessot recently retired from his position as senior physicist at the Harvard-Smithsonian Center for Astrophysics, where he served as principal investigator of the Hydrogen Maser Laboratory from 1969 and now serves as a research associate. His research group built all the hydrogen masers used in NASA's Deep Space Network and has supported radio astronomical Very Long Baseline Interferometry activities worldwide. He has worked on hydrogen masers since 1961 and did much to make the hydrogen maser the most stable oscillator available. Before joining Harvard-Smithsonian, he was manager of hydrogen maser research and development at Varian Associates/Hewlett-Packard (1960-1969). He was principal investigator for NASA's Gravity Probe-A experiment, which confirmed Einstein's predictions of the effects of relativistic gravitation on the rate of clocks at a precision of 70 parts per million. He currently works as a consultant for Kernco, a commercial provider of atomic frequency standards. In 1978, Dr. Vessot was awarded the NASA Medal for Exceptional Scientific Achievement. He received the IEEE Rabi Award in 1978 and the PTTI Distinguished Service Award in 2001.

John R. Vig is a research scientist and program manager at the U.S. Army's Fort Monmouth. His work has focused primarily on frequency control devices, with a specialty in quartz crystal oscillators. He is a fellow of IEEE and has received that organization's Cady Award. He is active in the IEEE Frequency Control Symposium, frequently serving in leadership roles, including chair of the Technical Program Committee for the 2002 international symposium. He has served as president of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society and is currently president of the IEEE Sensors Council.

B

Tutorial on PTTI Frequency Standards

ATOMIC FREQUENCY STANDARDS AND CLOCKS

General

Atomic frequency standards are all based on particular frequency resonances in, ideally, isolated atoms of an isotope of an element such as cesium-133, which happens to be the basis for the present definition of frequency or time interval. The term atom is used here, but for present purposes, it can also mean ion or molecule. All atoms of the same element and isotope are absolutely identical in structure and therefore have identical resonances and resonance frequencies. This is a fundamental fact of nature and is described by quantum mechanics. It explains why atomic frequency standards can be so accurate.

Quantum mechanically, isolated atoms have a number of energy levels, or states, determined by their structure. Atoms in a given state can be induced to make transitions to another state through interaction with an electromagnetic field. The interaction is not strong unless the frequency ν of the field is close to $\Delta E/h$, where h is Planck's constant and ΔE is the difference in energy of the two states. This is the basis for atomic resonances.

At room temperature isolated atoms are usually in the lowest state, called the ground state. The ground state may be split into a number of substates of small energy separation, called hyperfine splitting, by interactions of the atomic electrons with the nuclear magnetic moment. These substates, in turn, may be split by an applied magnetic field. These energy splittings are typically small compared with the thermal energy at room temperature, so the atoms are almost equally liable to be in any of these states. The frequencies associated with these hyperfine splittings are in the microwave or millimeter-wave range. Atoms with splitting in the ground state are typically used for microwave atomic frequency standards. They include hydrogen, the alkalis, and some singly ionized atoms such as mercury. Figure B.1 shows the energy levels in the ground state of atomic hydrogen as a function of external magnetic field.

If the atoms are excited to higher-energy electronic states, they relax with a characteristic relaxation time to some lower energy state by emitting electromagnetic radiation at frequency $\nu = \Delta E/h$. The

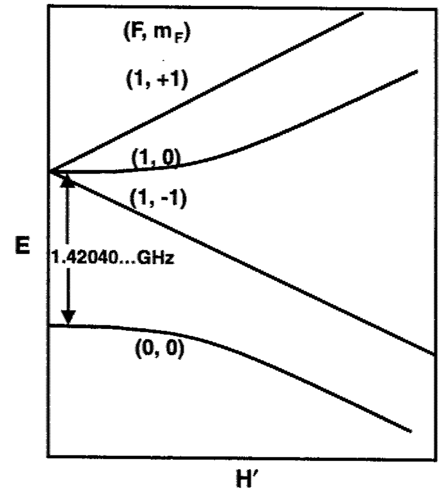

FIGURE B.1 Ground-state energy levels of atomic hydrogen as a function of magnetic H′. The transition used for the frequency standard is (0,0) – (1,0), which depends on magnetic field only in second order.

relaxation time from an excited state depends on the atomic structure and the energy of the state and varies from nanoseconds for moderate state energies and highly allowed transitions to seconds for what are called forbidden transitions. These transitions are in the optical, infrared, and ultraviolet ranges. Those with long relaxation times are useful for isolated atom optical frequency standards. The frequency linewidth $\Delta\nu$ associated with a transition is of the order $1/(\pi T)$, where T is the relaxation time.

The relaxation time for transitions between ground-state levels is typically years for isolated atoms, so the relaxation can be neglected for isolated atom microwave standards. However, in gas cell microwave standards or other standards in which atomic collisions occur, collisions shorten the relaxation time and determine the linewidth. In isolated atom microwave standards, the linewidth is roughly proportional to the reciprocal of the interaction time of the electromagnetic field with the atoms. This can be understood from Fourier transform relationships.

The quality factor of a resonance is $Q_l = \nu/\Delta\nu_l$, where $\Delta\nu_l$ is the linewidth determined by collisions, interaction time, or the natural linewidth, whichever gives the largest linewidth. The achievable accuracy (small numbers are desired here) of an isolated atom frequency standard (essentially no collisions) is proportional to $1/Q_l$, so a high-frequency ν and a small-linewidth $\Delta\nu_l$ are desired. This is what makes the optical standards attractive. Their accuracy can be orders of magnitude better than microwave standards.

With regard to the interaction with the electromagnetic field, atomic transitions to a higher energy state absorb a quantum of energy $h\nu$, called a photon, from the field. Transitions to a lower energy state add a photon to the field. This is simply conservation of energy.

Typically, there is a small, homogeneous, static magnetic field in the interaction region to provide what is called a quantization axis and also to separate magnetic-field-dependent states from those used for the frequency standard. The frequency standard states usually have only a small, second-order dependence on magnetic field.

A technique is provided to detect either the transition probability of the atom or the change in the electromagnetic field and convert it to an electrical signal. This allows the atomic resonance to be used

in a frequency standard. To get a large signal-to-noise ratio, necessary for good short-term stability, as described below, many atoms must be interrogated per unit time, particularly for microwave standards. Since in equilibrium atoms are distributed essentially uniformly in the ground state, on interaction with the electromagnetic field roughly as many upward transitions as downward transitions would occur, so very little signal can be observed. A technique for state-selection must be used to prepare the atoms to be mainly in one state before (or during) the interaction. This produces the necessary large signal.

The functions of state selection, detection, atom containment, and means for interaction with the electromagnetic field form the atomic resonator and state detector. There must also be magnetic shielding and means for supplying the required small magnetic field, typically between 1 and 50 milligauss. A typical electrical signal from the resonance as a function of frequency is shown in the lower part of Figure B.2. It is used as described below, in "Passive Standards."

If a number of atoms are state-selected or optically pumped to be in the upper level in the ground state or an excited state, and if they are in a suitable, low-loss cavity resonator, an oscillation at the transition frequency can build up. Here, the atoms supply energy to the cavity field by making transitions to the lower level. The atoms in turn are stimulated to make the transition by the cavity field. The oscillation builds up to where the power (energy per unit time) supplied by the atoms is equal to the power dissipated in the cavity and any load connected to the cavity. This is the principle of maser and laser devices. The maser is used as described below, in "Active Standards."

Atomic frequency standards are so accurate that relativistic effects must be taken into account. For example, a frequency standard 1 km above the surface of the oceans is 1.1×10^{-13} higher in frequency than one at sea level due to the change in gravitational potential. Velocity effects are also important. The velocity of the atoms in a cesium beam standard at room temperature causes it to be about 1×10^{-13} lower in frequency than a standard built with stationary atoms. Both gravitational and velocity effects must be taken into account for the standards in GPS satellites.

Passive Standards

The atomic resonator described above is used to make a microwave frequency standard, as shown in Figure B.2. The goal is to produce a useful output signal the frequency of which is tied to the atomic resonance at ν_0.

Since the resonance is, to a good approximation, an even function of frequency about ν_0, it is impossible to stabilize directly to the peak value of the resonance with any accuracy. The derivative of the signal with respect to frequency would work since it vanishes at ν_0. The technique most often used to approximate this is to frequency modulate the microwave excitation signal, often with a square wave to the inflection points of the resonance. The electrical output signal will then contain a signal at the frequency of the modulation oscillator roughly proportional to the error in the average frequency of the microwave excitation and whose phase depends on the direction of the error. This signal is detected in a synchronous detector and gives a DC and low-frequency (baseband) error signal that is amplified and filtered and applied to the electronic frequency control (EFC) input of a voltage-controlled oscillator (VCO), also known as the local oscillator (LO), whose frequency output is converted to the microwave excitation frequency by the frequency synthesizer, which effectively multiplies the LO frequency by a rational number. This is a frequency servoloop that forces the average microwave excitation frequency to be at the center of the atomic resonance. When the system is locked, the frequency output 1 is the atomic resonance frequency divided by the synthesizer fraction, which may be chosen along with the LO frequency to produce a useful frequency such as 10 MHz. The fractional frequency resolution of the

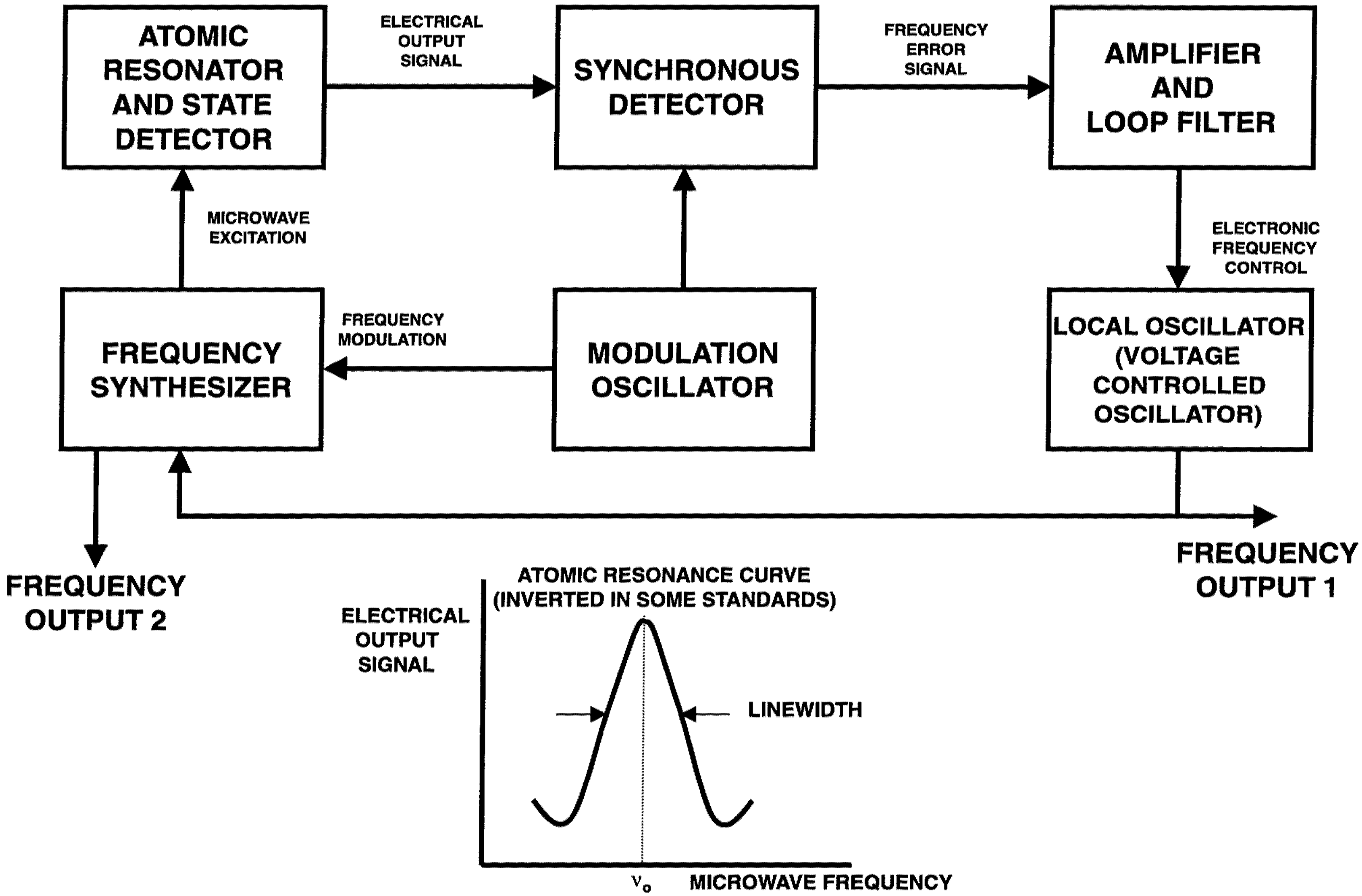

FIGURE B.2 Block diagram of a passive microwave atomic frequency standard.

synthesizer can easily be 1×10^{-15} or better. The synthesizer may also produce another useful output, frequency output 2.

This type of servoloop acts as a low-pass filter to the atomic resonator frequency noise and a high-pass filter to the LO frequency noise. The loop time constant is chosen to optimize overall frequency stability performance. Noisier local oscillators require a longer loop time constant, which is often undesirable.

The frequency stability, characterized by the Allan deviation and determined by the noise in the atomic resonator, is approximately $1/(S/N\ Q_1\tau^{1/2})$, where S/N is the effective electrical signal-to-noise ratio in a 1 Hz bandwidth centered at the modulation frequency at the output of the resonator, Q_1 is the quality factor mentioned above, and τ is the averaging time of the measurement. Because this is low-pass filtered by the loop, it applies for times that are long compared with the loop time constant until other effects such as flicker noise or aging take over. It is clear that a large S/N and Q_1 are desirable. In a good design, the noise of the atomic resonator will be dominant.

The frequency stability at times short compared with the loop time constant, as mentioned above, is determined by the LO. There is also an effect due to frequency noise at the second harmonic of the modulation frequency that effectively adds to the atomic resonator noise. Low-noise atomic resonators thus require good LOs.

In modern standards, much of the electronics is digital, and microprocessors are used for much of the control and filtering functions, providing greatly improved performance. Some of the environmental effects will be discussed below.

Figure B.2 can also apply to optical frequency standards. The LO in that case is a narrow linewidth, very stable laser, which is a formidable engineering task. Optical pumping with lasers does most of the state preparation and transition detection. Accurate transfer of optical frequencies to microwave frequencies is very important and is discussed later.

Active Standards

Figure B.3 shows a typical active microwave atomic standard such as a hydrogen maser. The power output of the atomic oscillator is typically quite small, on the order of picowatts, and its frequency is very susceptible to changes in output loading. For these reasons, the signal is amplified and heterodyned down to some convenient frequency by mixing with an output from the synthesizer. The signal is compared in phase with another output from the synthesizer. The phase error is amplified and filtered and applied to the EFC of a LO, which in turn supplies the reference frequency for the synthesizer. This is a phase-lock loop that forces the LO to run at a frequency that is a rational fraction, determined by the synthesizer, of the atomic oscillator. The loop time constant is chosen to provide overall best noise performance.

At the present time, there are no really accurate active optical frequency standards (lasers). The reasons for this are the high optical gain and low optical cavity loss required to get oscillation. The high optical gain requires many atoms with low Q_1. This, coupled with the low cavity loss, makes the laser oscillate close to the cavity resonance frequency rather than the atomic resonance frequency.

Clocks

A clock consists of two parts: first, a good oscillator such as the atomic standards described here and second, a means for counting the cycles of the oscillator or, equivalently, monitoring its elapsed phase and converting the phase to convenient units of time. In a mechanical clock, the oscillator is the

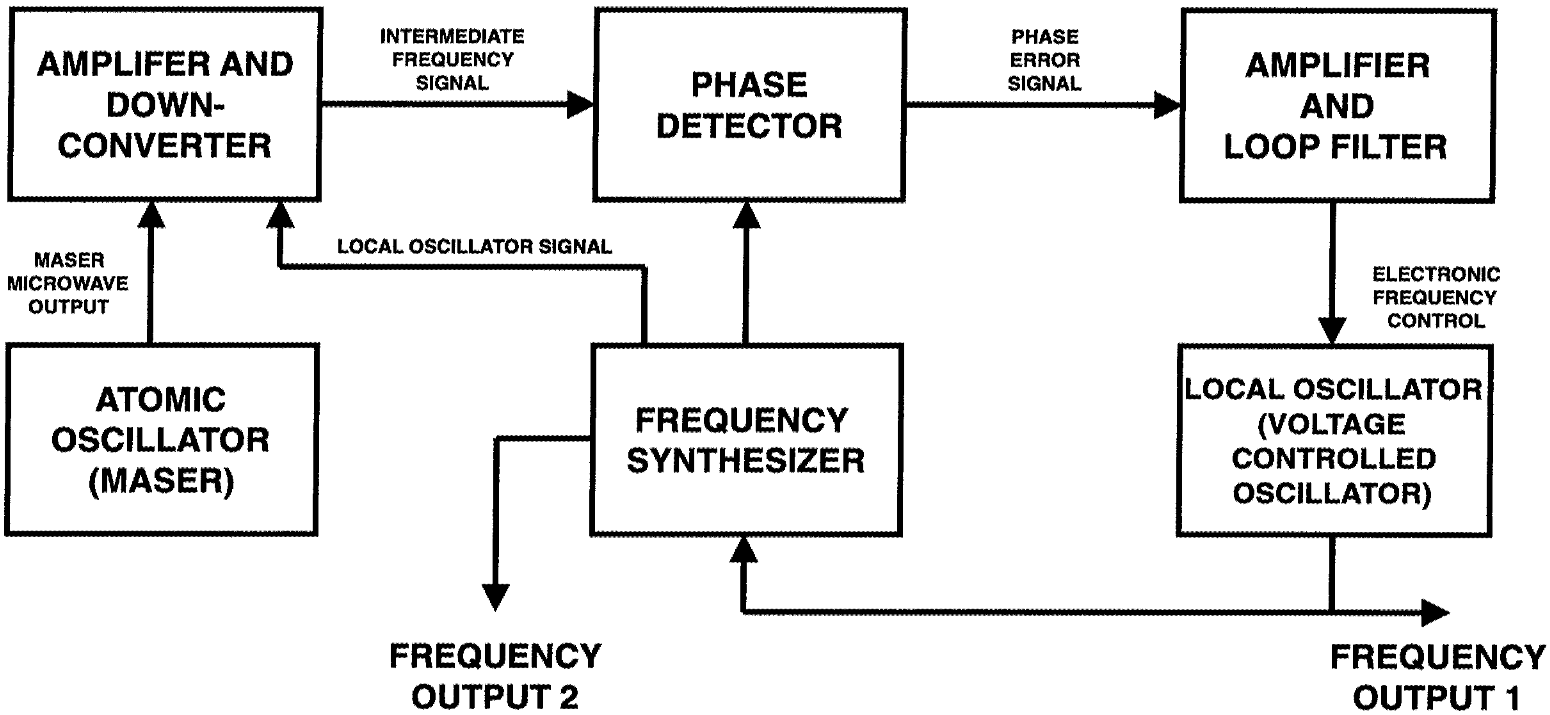

FIGURE B.3 Block diagram of an active microwave atomic standard, such as a hydrogen maser.

pendulum or balance wheel and the elapsed-phase device is the combination of gear train and clock hands. The elapsed-phase device in atomic clocks is the frequency synthesizer and an electronic counter.

The clock's time must be set initially to agree with some chosen time scale; this is synchronization. The clock's frequency must also be set so that its rate matches the chosen time scale; this is syntonization. An error in synchronization gives a time offset to the clock. An error in syntonization gives a magnitude of time error in the clock that increases linearly with passing time (assuming the clock rates are constant). As mentioned above, in the most accurate clocks relativistic effects are very important and must be taken into account.

MICROWAVE ATOMIC FREQUENCY STANDARDS

Laboratory

Cesium Beam

These standards use a beam of cesium-133 that is state separated and detected either by magnetic deflection or optical pumping. Optically pumped standards give the best performance. The state-separated atoms are interrogated by an applied microwave magnetic field in a cavity, configured to subject them to two microwave regions leading to a double microwave pulse in time known as Ramsey interrogation (named after Norman Ramsey, who won a Nobel Prize for his work in atomic frequency standards). Such a cavity is called a Ramsey cavity. If the microwave frequency is at the atomic hyperfine resonance (~9192.631 MHz) and the field is at the correct amplitude, the probability of transitions in the ground state is maximized. The atoms in the beam are then subjected to detection of the probability of transition leading to an output electrical current proportional to the transition probability. This is used in a servo system like that shown in Figure B.2 to keep the frequency of the microwave excitation at the center of the probability versus frequency dependence. Useful output frequencies are obtained by frequency synthesis. The frequency width of the atomic resonance is proportional to the inverse of the time between the microwave pulses and is on the order of 70 Hz in typical laboratory systems, and the accuracy capability is about $\pm 1 \times 10^{-14}$. The relativistic shift is a few parts in 10^{13} for the thermal beam in the apparatus, to which must be added the shift due to elevation above sea level.

Cesium Fountain

In this recently developed standard, cesium atoms are cooled and trapped at microkelvin temperatures by laser cooling and then state selected by optical pumping. Balls of these trapped atoms are launched upward sequentially and pass through a microwave cavity, where they interact with the applied microwave magnetic field. They continue upward for perhaps a meter and then fall back under gravity through the microwave cavity a second time, giving the double microwave pulse for Ramsey interrogation. The probability of state transition is then determined optically and appears as an electrical signal, which is used as described above to control the frequency of the microwave excitation. The frequency width of the atomic resonance is on the order of 1 Hz in typical fountains because of the long time between the microwave pulses, leading to an accuracy of about ± 1 part in 10^{15}, much better than the beam standards. The shift due to relativistic effects in the apparatus is about 4×10^{-17} for a 1-meter toss height. This is much smaller than the shift in the cesium beam. The shift due to elevation above sea level must be added to this. The main limitation of accuracy is the frequency shift caused by cesium-cesium collisions

and uncertainty in the local gravitational potential. The collisional shift is much smaller with rubidium, and work on a rubidium fountain standard is ongoing.

Cesium fountain standards have been and are being built in a number of laboratories around the world, including the USNO.

Trapped Mercury Ion

In the most advanced microwave trapped-mercury-199 ion frequency standard on which work is being done, ions are confined in a linear radio-frequency quadrupole trap partitioned electrically along its length so that ions can be shuttled from one end to the other. Ions are moved to one end of the extended trap for optical state selection and detection and then moved to other end for the atomic resonance, where interaction with the approximately 40.5-GHz electromagnetic field takes place. Helium at a pressure of 10^{-5} torr is used to cool the ions so that a large number can be trapped. In addition, the interaction time with the microwave field can be long, leading to a narrow linewidth.

Optical pumping with a mercury-202 lamp is used for state selection and detection. The spectrum of the mercury-202 ion is such that the mercury-199 ions are pumped into the lower hyperfine state. Detection is accomplished by monitoring the fluorescence with photomultiplier tubes after interaction with the microwaves. Maximum fluorescence occurs when the microwave frequency matches the ionic resonance if the microwave amplitude and interaction time are optimized.

The electronics for the standard are similar to that shown in Figure B.2. With the large number of trapped ions and the long interaction time, very good short-term stability should be achieved, about $4 \times 10^{-14}\tau^{-1/2}$, which requires an extremely good local oscillator. The accuracy of this standard should also be good. There are relativistic effects due to the velocities of the ions in the radio-frequency trap. There is also a small frequency shift due to collisions with the helium. This shift can be estimated by varying the helium pressure, observing the frequency changes, and extrapolating to zero pressure.

Hydrogen Maser

Molecular hydrogen is dissociated into atoms and state separated in a magnetic field so that the higher energy state atoms are directed into a suitably coated bulb inside a high quality-factor (Q_c) cavity resonant at the hyperfine frequency (~1420.4 MHz). If the number of atoms in the bulb and in the cavity Q_c are both high enough, oscillation can take place in the cavity by stimulated emission of the atoms at the hyperfine frequency. This oscillation is coupled out and used to phase-lock a voltage-controlled oscillator/frequency synthesizer combination to provide the maser frequency output. There are frequency-pulling effects associated with (1) mistuning of the cavity with respect to the atomic hyperfine frequency and (2) collisions with the coated walls, known as wall shift. Some of the masers have a technique for automatically tuning the cavity to remove the cavity pulling effect. The short-term frequency stability of the hydrogen maser is excellent, but its accuracy is inferior to that of the cesium devices owing to the uncertainty associated with the wall shift. There is also a small frequency aging effect caused by changes of the wall shift with time. The relativistic shift due to the velocity of the hydrogen atoms, called second-order Doppler shift, is about -1.4×10^{-13} per kelvin, so temperature must be very carefully controlled to achieve good stability.

Work is proceeding on a cryogenic hydrogen maser operating at 0.5 K. In this maser, the wall coating is liquid helium in the superfluid state. The frequency stability may be as good as 1×10^{-18}.

There is also a passive hydrogen maser in which the hyperfine transition is interrogated by a signal injected into the cavity. Early work was done at NIST, and there was an effort, later abandoned, to

commercialize the device in the United States. Such masers are available commercially now from Russia. The main advantage of the passive maser is its much smaller frequency pulling due to cavity mistuning. However, the short-term stability is much poorer than that of the active maser.

Rubidium Gas Cell

Rubidium-87 atoms, along with a buffer gas in a glass cell surrounded by a microwave cavity, are optically pumped by light from a rubidium lamp/filter combination to perform state selection between the hyperfine levels. The transmitted pumping light is monitored by a photodetector to provide the electrical output signal. In the absence of microwave excitation at the hyperfine resonance frequency (~6834 MHz), equilibrium between the optical pumping and hyperfine relaxation gives a particular transmitted light intensity. If microwave excitation at the resonance frequency is present, additional hyperfine transitions are induced, which allows more optical pumping to take place. Then, more pumping light is absorbed, and the transmitted light and output signal decrease. The frequency width of this resonance is typically a few hundred hertz.

The buffer gas confines the rubidium atoms, largely preventing collisions with the cell walls and also reducing the Doppler width. However, collisions of rubidium atoms with buffer gas atoms cause a frequency shift that depends on pressure, temperature, and gas mixture. In addition, there is a frequency shift due to the simultaneous irradiation of the rubidium atoms by the pumping light and the microwave excitation. This so-called light shift depends on both light intensity and spectral distribution. Thus the rubidium gas cell standard has much poorer accuracy than the cesium beam standard and has frequency aging due to drifts in the light intensity, diffusion of helium into the cell, and other changes in the buffer gas that are due to diffusion from the cell walls. However, if the rubidium gas cell is properly designed, its short-term stability can be very good An Allan deviation of $1 \times 10^{-13}\tau^{-1/2}$ has been demonstrated at NIST, which believes that an order of magnitude improvement is possible. This would be a very good local oscillator for laboratory microwave frequency standards.

Rubidium in a gas cell can also oscillate as a maser if the cavity Q is high enough and the spectrum of the optical pumping source is appropriate. Work was done on this in the late 1960s. Work is ongoing on a double-bulb version in which the optical pumping is done in one of the bulbs outside the microwave cavity and the maser action takes place in the other bulb, which is inside the microwave cavity and connected to the pumping bulb. This arrangement virtually eliminates the light shift. The power output of the rubidium maser is considerably larger than that of the hydrogen maser. It might serve as an LO for a rubidium fountain standard.

SPACEBORNE

Cesium Beam

The spaceborne cesium beam standards used in, for example, GPS satellites are very similar to the magnetically state-selected laboratory devices described above but have much shorter beam tubes, leading to a much larger linewidth and a lower signal-to-noise ratio, with consequent lower accuracy and poorer short-term stability. Great attention is paid to ruggedness, reliability, small size, and low power.

There is at least one U.S. effort to develop a small, optically pumped beam tube, which should give improved short-term stability. The Navy is supporting this work.

Rubidium Gas Cell

The spaceborne rubidium gas cell standard is similar to the laboratory rubidium standard described above, except that small size, ruggedness, long life, and moderately good short-term stability are emphasized. In the block IIR GPS satellites, these standards are providing better short-term stability than the cesium beam standards. In MILSTAR and the Advanced Extremely High Frequency (AEHF) military satellite communications systems, the emphasis is again on low power, small size, and environmental issues.

Clocks on the ISS

The primary atomic reference clock in space (PARCS) standard is an ongoing joint effort of NIST, JPL, University of Colorado, and the Smithsonian Astrophysical Observatory, with funding from NASA. It uses laser cooling and trapping to generate and launch balls of cold, state-selected cesium atoms in a way similar to that described above for the cesium fountain. However, in the microgravity environment of space, the balls are in free, unaccelerated motion and are directed through a Ramsey cavity, like that in the beam apparatus described above, to achieve Ramsey interrogation. The atoms have very low velocity, so that the time between their encounters with microwave pulses is about 10 seconds, leading to a very small linewidth, on the order of 0.1 Hz. The expected accuracy is on the order of $\pm 1 \times 10^{-16}$. This standard will require an excellent LO. Present plans are to use the Smithsonian spaceborne maser discussed below. PARCS will be used, not only as an excellent standard in space but also for a number of scientific experiments.

The rubidium atomic clock experiment (RACE), a joint project between Pennsylvania State University and JPL, is a spaceborne rubidium cold-atom clock expected to have an accuracy of ± 1 part in 10^{17}. It is to fly on the ISS after PARCS, circa 2007. It will be used to improve the classic clock tests of general relativity.

The atomic clock ensemble in space (ACES) is a European Space Agency mission on the ISS. It consists of a laser-cooled cesium clock that, like PARCS, takes advantage of the microgravity environment to achieve low linewidth and high accuracy. It is scheduled to fly at about the same time as PARCS (2005 or 2006).

Hydrogen Maser

There was an effort at Hughes to develop a small, spaceborne hydrogen maser a number of years ago, but the effort was abandoned. The Smithsonian Astrophysical Observatory also had a program that is now again active. This maser weighs about 100 kg and has demonstrated stability of 5×10^{-15} at 100 seconds averaging time. It is planned to be used as the LO for the PARCS mentioned above.

Commercial

Cesium Beam

There are five commercial cesium beam standards available at the present time, three of them made by U.S. companies. They are all similar to the magnetically state-selected laboratory standard described above but have shorter beam tubes and consequent larger linewidth. They vary in their accuracy, short-term stability, environmental performance, and price. The best have an accuracy of plus or minus a few

parts in 10^{13} and Allan deviation of about $8 \times 10^{-12}\tau^{-1/2}$. One application is as clocks in international laboratories contributing to the international atomic time scale (for example, the USNO uses about 40 units in its time-scale ensemble). Another is the clock ensemble at the GPS ground control station that uploads time to the GPS satellites. They are also used aboard Navy ships, and there are a number of communications applications.

As mentioned above, there is at least one U.S. effort under way to develop a small, optically pumped beam tube, which should give improved short-term stability. The Navy is supporting this work.

Rubidium Gas Cell

This is by far the best-selling commercial atomic standard, with sales in excess of 40,000 units per year by the two main U.S. suppliers. The units are all very similar to the rubidium units described above. Emphasis is on low cost and moderately small size (~100 cm^3). Their main use is in cellular base stations and other telecommunications applications.

Hydrogen Maser

There is at present only one U.S. commercial supplier of active hydrogen masers. Both passive and active masers are also available from Russia. They are being used in increasing numbers as members of time-scale ensembles because they have excellent short-term stability.

OPTICAL FREQUENCY STANDARDS

Mercury Ion

An optical frequency standard is being developed at NIST in which a single mercury-199 ion is contained in a quadrupole trap. This ion has a narrow (~1-Hz) optical transition at about 1.06×10^{15} Hz that is interrogated by a highly stabilized laser at 564 nm that is frequency doubled to reach the optical transition. Work done so far indicates that accuracy considerably better than $\pm 1 \times 10^{-16}$ is achievable.

Calcium

NIST is working on an optical frequency standard using trapped calcium atoms. The clock transition frequency is about 4.54×10^{14} Hz with a narrow natural linewidth of about 400 Hz. About 10^6 atoms are trapped in a magneto-optic trap (MOT). The trap is turned off, and then two separate pulsed lasers are used to interrogate the atoms and detect the transition probability. The trap is then turned on again and the process repeated. Because the linewidth is much larger than that of the mercury ion standard, the achievable accuracy is much poorer. However, the large number of atoms being interrogated gives very good short-term stability.

Other

A number of other ions and atoms are also under investigation as candidates for optical standards. Among these are single trapped ions of indium and ytterbium. Work is also being done on standards using trapped neutral atoms of strontium. Neutral atoms, like the calcium atoms mentioned above, have the advantage that many can be held in the trap, giving good signal-to-noise ratio and, consequently,

good short-term stability. However, the transitions currently being investigated in neutral atoms have much larger linewidths than those of the ions, so the achievable accuracy is much poorer.

COHERENT POPULATION TRAPPING

Although discussed in the early 1970s, this approach has only recently received much attention, mainly because lasers suitable for pumping are now available. Several groups are now working in this field.

The excitation of the atoms in a cell is all optical, using two coherent optical signals to pump on two ground-state levels of the atoms. If the optical signals are at the frequencies to pump to a single excited state and the difference between their frequencies is at the resonance frequency between the ground states, the atoms are trapped in a coherent superposition of the ground states. Under these conditions, the excited state is not populated, and the fluorescence disappears. No microwave cavity is needed in the case of a passive device, so it is much easier to miniaturize. Monitoring the fluorescence or the transmission through the cell does the resonance detection for this type of passive microwave standard.

If a cavity tuned to the resonance frequency between the ground states surrounds the cell, microwave power radiated by the atoms can be detected. The frequency of this radiation is the difference frequency between the optical signals.

QUARTZ OSCILLATORS

The simplified circuit diagram in Figure B.4 shows the basic elements of a modified Pierce crystal oscillator. A quartz crystal acts as a stable mechanical resonator, which, by its piezoelectric behavior and high Q, determines the frequency generated in the oscillator circuit. The crystal resonator (also called the "crystal unit") is also the primary determinant of frequency stability in the oscillator.

In the manufacture of quartz resonators, wafers are cut from a quartz crystal along precisely controlled directions with respect to the crystallographic axes. The properties of the device depend strongly on the angles of cut. After shaping to required dimensions, metal electrodes are applied to the quartz wafer, which is mounted in a holder structure. The assembly is hermetically sealed, usually into a metal or glass enclosure.

To cover the wide range of frequencies, different cuts vibrating in a variety of modes can be used. When cut along certain directions, resonators whose temperature coefficient is zero may be produced (the resonator frequencies still vary slightly with temperature; the resonators possess zero temperature coefficient at two specific temperatures only). For PTTI applications, the AT-cut and SC-cut are used, both of which vibrate in the "thickness shear" mode. For the applications that demand the highest precision, the SC-cut has important advantages over the AT-cut; however, the SC-cut is more difficult to produce, so it is generally more expensive than the AT-cut.

The three categories of crystal oscillators, based on the method of dealing with the crystal unit's frequency versus temperature (f versus T) characteristic, are the uncompensated crystal oscillator, XO, the temperature-compensated crystal oscillator, TCXO, and the oven-controlled crystal oscillator, OCXO. A simple XO does not contain means for reducing the crystal's f versus T variation. A typical XO's f versus T stability may be ±25 parts per million (ppm) over a temperature range of –55°C to +85°C.

In a TCXO, temperature-dependent reactance variations produce frequency changes that are equal and opposite to the frequency changes resulting from temperature changes—that is, the reactance variations compensate for the crystal's f versus T variations. For example, the output signal from a

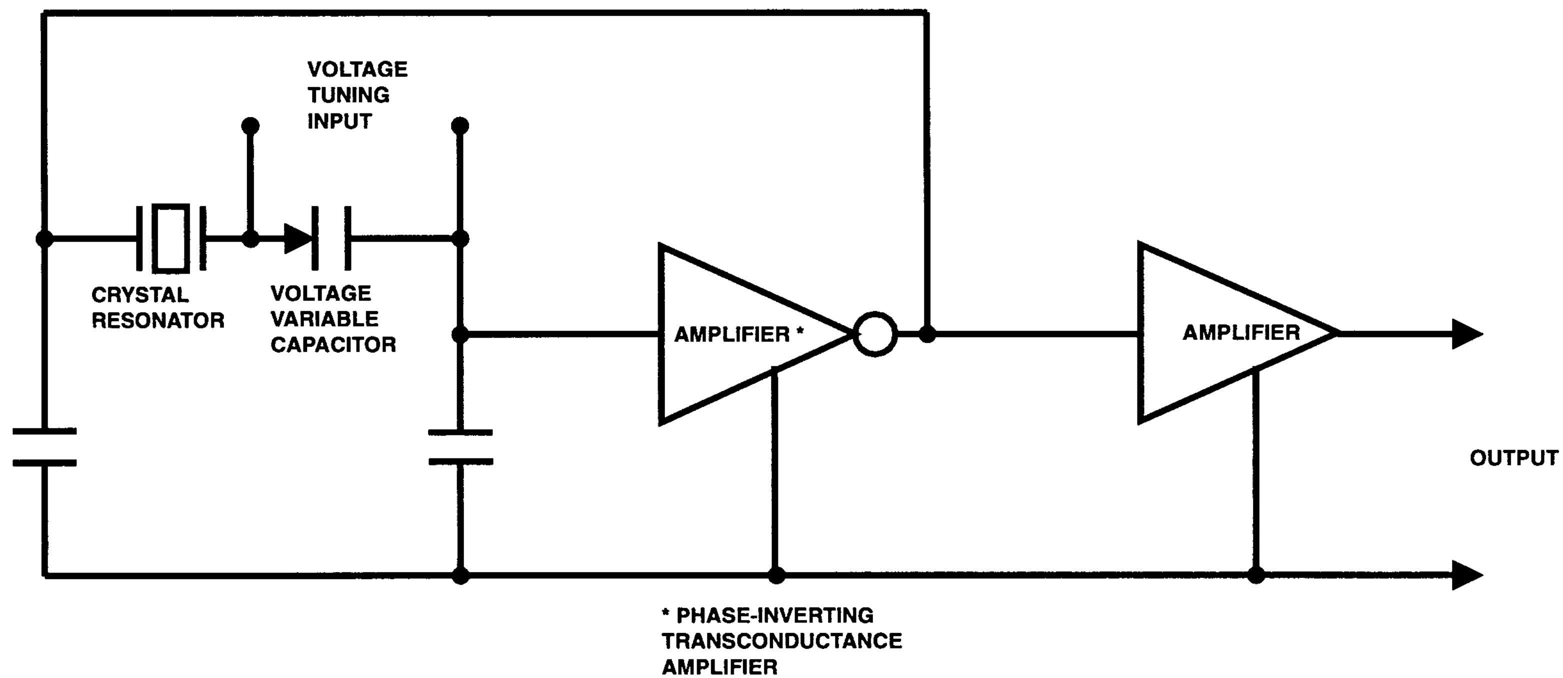

FIGURE B.4 The basic elements of a modified Pierce crystal oscillator.

temperature sensor (a thermistor) can be used to generate a correction voltage that is applied to a voltage-variable reactance (a varactor) in the crystal network. TCXOs generally use AT-cut crystal resonators. Analogue TCXOs can provide about a 20-fold improvement over the crystal's f versus T variation. A good TCXO may have an f versus T stability of ±1 ppm over a temperature range of –55°C to +85°C. Hysteresis, i.e., the nonrepeatability of the f versus T characteristic, is the main TCXO stability limitation.

In an OCXO, the crystal unit and other temperature-sensitive components of the oscillator circuit are maintained at an approximately constant temperature in an oven. The crystal is manufactured to have an f versus T characteristic that has zero slope at or near the desired oven temperature. To permit the maintenance of a stable oven temperature throughout the OCXO's temperature range (without an internal cooling means), the oven temperature is selected to be about 15°C above the maximum operating temperature of the OCXO. OCXOs can provide more than a 1,000-fold improvement over the crystal's f versus T variation. The best OCXOs may have an f versus T stability of $\pm 1 \times 10^{-10}$ over a temperature range of –55°C to +85°C. OCXOs require more power and are larger than and more expensive than TCXOs.

A special case of a compensated oscillator is the microcomputer-compensated crystal oscillator, MCXO (in advanced development). The MCXO minimizes the two main factors that limit the stabilities achievable with TCXOs: thermometry and the stability of the crystal unit. Instead of a thermometer that is external to the crystal unit, such as a thermistor, the MCXO uses a more accurate self-temperature-sensing method. Two modes of an SC-cut crystal are excited simultaneously in a dual-mode oscillator. The two modes are combined such that the resulting beat frequency is a monotonic (and nearly linear) function of temperature. The crystal thereby senses its own temperature. To reduce the f versus T variations, the MCXO uses digital compensation techniques: pulse deletion in one implementation and direct digital synthesis of a compensating frequency in another. A good MCXO may have an f versus T stability of $\pm 2 \times 10^{-8}$ over a temperature range of –55°C to +85°C. As in TCXOs, hysteresis is the main MCXO stability limitation; however, the crystal resonators used in the MCXO exhibit significantly smaller hysteresis than the resonators used in TCXOs.

LOCAL OSCILLATORS

Quartz, Rubidium, and Hydrogen

Relatively simple quartz oscillators as described above can serve as LOs for many of the lower-performing atomic standards. The best commercial cesium beam standards require a good OCXO. Since the servoloop controls the low-frequency behavior of the LO, slow changes in its frequency caused by temperature variations or aging are removed from the output of the standard. This is particularly true if the loop filter contains at least two digital integrators. However, the LO determines the high frequency or very short-term performance of the standard. The oscillator may be chosen to meet this requirement, or another low-noise oscillator may be phase-locked to the standard's output or to the output after frequency multiplication.

Quartz oscillators are too noisy as LOs to realize the full capability of the high-performance laboratory microwave atomic standards. This is discussed further below. In some cases, a high-performance laboratory rubidium standard optimized for stability can serve the purpose. Hydrogen masers are also used as LOs. As an example, it is planned for the spaceborne PARCS cesium standard to use the spaceborne hydrogen maser mentioned above.

Microwave

A number of very high-performance microwave oscillators have been built using sapphire cavities. Some of these operate in what are called whispering gallery modes, in which the electromagnetic field is confined in the sapphire. These can have very high Q at cryogenic temperatures and, if some noise reduction techniques are used, can make an excellent, but expensive and complex, LO for a high-performance microwave standard. Oscillators of this type were first developed at Stanford University and at JPL. This technology is currently being pursued at the University of Western Australia and at JPL, and it has been used to demonstrate the highest performance of advanced atomic clocks, such as the mercury ion standard and the cesium fountain. A room-temperature version of the whispering-gallery-mode sapphire oscillator has been commercialized in Australia, which produces the highest spectral purity at 10 GHz by extensive use of the carrier-suppression technique.

Work is under way on an optoelectronic oscillator using a fiber-optic delay line. The optical signal input to the delay line is modulated by a microwave signal that is an amplified, filtered signal obtained from a high-speed optical detector at the output of the delay line. With sufficient gain, the system oscillates at a frequency such that the roundtrip phase is an integer multiple of 2π. The equivalent Q of this system is πft, where f is the operating frequency and t is the delay of the line. For a 10-GHz oscillator with a 4-km delay line, the Q is about 6×10^5. This type of oscillator may hold promise as an LO for high-performance microwave standards.

Laser

The only LO suitable for probing very narrow optical transitions is a highly stabilized laser. Probably the best have been built at NIST for the mercury-199 ion optical transition. They consist of a dye laser stabilized by a rugged, large, very-high-Q optical cavity at 564 nm. Two of them have been built so that the linewidth can be measured by heterodyning them against each other. The measured optical linewidth is on the order of 0.1 Hz. Extreme care in terms of vibration and acoustic isolation is necessary to achieve this performance.

Local Oscillator Effects

Besides the noise effects of the LO mentioned above, there are other effects to consider. One of these is frequency noise density of the modulation frequency in passive standards at even harmonics, particularly the second harmonic. Depending on the type of resonator, the modulation waveform, and the synchronous detector, various amounts of the noise are downconverted to baseband and added to the noise of the atomic resonator. This is one of the main limitations of LO for high-performance atomic resonators.

Another effect involves amplitude modulation of the atomic resonator output that is coherent with frequency modulation of the LO. This can occur, for example, in atomic beam standards as a result of changes in the gravitational acceleration direction caused by motion of a vehicle. Both the beam tube output and the crystal oscillator LO frequency can depend on the orientation in the gravitational field. Frequency components in this modulation higher than the loop bandwidth can cause a frequency error. The French navy first noticed this effect. It can be reduced by making the loop time constant short and having the mechanical layout such that the most sensitive axes of the atomic resonator and the LO are orthogonal.

CONNECTION BETWEEN MICROWAVE AND OPTICAL REGIONS

Until recently, the absolute connection between microwave and optical frequencies, a range of four to five decades, required chains of phase-locked oscillators, many of them complex lasers. The equipment often filled rooms and would not function for very long periods. Very skilled people were needed to build and run them. Also, only a very small range of optical frequencies could be covered without having to redesign the whole chain.

The technique of using regularly pulsed lasers to generate a comb of optical frequencies has been known for a long time. It follows from Fourier analysis that a uniform series of pulses in time spaced by τ leads to a uniform series of spectral lines in the frequency domain spaced by frequency $1/\tau$. However, unless there is something that constrains the optical phase to be the same from pulse to pulse, the origin of the spectral lines is offset from zero by a frequency $\Delta\phi/2\pi\tau$, where $\Delta\phi$ is the change in phase from pulse to pulse in radians. Therefore, all the comb frequencies are offset by the same amount, which is in general unknown.

What is new is that a technique has been invented that allows the measurement and control of this offset frequency so that the absolute frequencies of the comb can be determined in terms of the pulse frequency, $1/\tau$, and the comb offset frequency. If these are measured or determined by, for example, a microwave frequency standard, the optical frequencies are known with the same accuracy (already tested to about $\pm 1 \times 10^{-17}$). By locking one of the comb lines to an optical frequency standard, a microwave frequency is generated that has the same accuracy as the optical standard.

The technique for measuring and controlling the offset frequency involves broadening the comb spectrum with a nonlinear optical fiber so that it extends over a two-to-one frequency range, an octave. A group of lines from the low-frequency end of the comb is frequency doubled and frequency subtracted from a group of lines at twice the frequency of the first group. The result can be shown to contain a signal at the comb-offset frequency, thus allowing its frequency to be measured or controlled.

The system can easily handle any optical frequency in the range of the comb. It is a simple and accurate way of connecting the microwave and optical frequency ranges. A number of laboratories in the United States, including NIST, are already building such combs, which are critical to realizing the performance capabilities of the new optical frequency standards as well as to measuring their frequencies.

C

Acronyms and Abbreviations

ACES	atomic clock ensemble in space
AEHF	advanced extremely high frequency
AMO	atomic, molecular, and optical
AMRAAM	advanced medium-range air-to-air missile
BAW	bulk acoustic wave
BEC	Bose-Einstein condensate
C3	command, control, and communications
C3I	command, control, communications, and intelligence
CAD	computer-aided design
CEC	cooperative engagement capability
CPT	coherent population trapping
DARPA	Defense Advanced Research Projects Agency
DDR&E	Director of Defense Research and Engineering
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EFC	electronic frequency control
FDOA	frequency difference of arrival
FEM	finite element model
GPS	Global Positioning System

IEEE	Institute of Electrical and Electronics Engineers
IFCS	International Frequency Control Symposium
IFF	identification, friend or foe
ISS	International Space Station
JDAM	joint direct-attack munition
JHU/APL	Johns Hopkins University, Applied Physics Laboratory
JILA	Joint Institute for Laboratory Astrophysics
JPL	Jet Propulsion Laboratory
JSTARS	joint surveillance target attack radar system
JTIDS	joint tactical information distribution system
LITS	linear ion trap standard
LLNL	Lawrence Livermore National Laboratory
LO	local oscillator
LORAN	long-range navigation
MCXO	microcomputer-compensated crystal oscillator
MEMS	microelectromechanical system
MILSTAR	military strategic and tactical relay
MMIC	microwave/millimeter-wave monolithic integrated circuit
MOT	magneto-optic trap
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NAVSPASUR	Naval Space Surveillance System
NIST	National Institute of Standards and Technology
NPL	National Physical Laboratory (Great Britain)
NRC	National Research Council
NRL	Naval Research Laboratory
NSF	National Science Foundation
OEO	optoelectronic oscillator
ONR	Office of Naval Research
OPNAV	Office of the Chief of Naval Operations
OXCO	oven-controlled crystal oscillator
PARCS	primary atomic reference clock in space
ppm	parts per million
PTTI	precision time and time interval
RACE	rubidium atomic clock experiment
R&D	research and development
rms	root mean square
RPV	remotely piloted vehicle

SABER	situational beacon and reply (system)
SAM	self-assembled monolayer
S&T	science and technology
SAW	surface acoustic wave
SECNAV	Secretary of the Navy
SINCGARS	single-channel ground and airborne radio system
SPAWAR	Space and Naval Warfare Systems Command
STAR	special technology area review
TARA	technology area review and assessment
TCXO	temperature-compensated crystal oscillator
TDMA	time division multiple access
TDOA	time difference of arrival
TWSTT	two-way satellite time transfer
UERE	user equivalent range error
USAF	U.S. Air Force
USNO	U.S. Naval Observatory
UTC	Coordinated Universal Time
VCO	voltage-controlled oscillator
XO	crystal oscillator

D

Glossary

"Overall frequency accuracy" and "clock accuracy" are defined by military specification MIL-PRF-55310D as follows:

> *6.4.33 Overall frequency accuracy.* The maximum permissible frequency deviation of the oscillator frequency from the assigned nominal value due to all combinations of specified operating and non-operating parameters within a specified period of time. In the general case, overall accuracy of an oscillator is the sum of the absolute values assigned to the following:
>
> a. The initial frequency-temperature accuracy . . .
> b. Frequency-tolerances due to supply voltage changes . . . and other environmental effects . . .
>
> Total frequency change from an initial value due to frequency aging . . . at a specified temperature.
>
> *6.4.4 Clock accuracy.* The degree of conformity of a clock's rate with that of a time standard. Clock accuracy [is] expressed as the worst case time error that can accumulate over specified operating conditions and over a specified duration following clock synchronization (e.g., 10 milliseconds per day) . . .

Stability is the maximum deviation of the oscillator frequency due to operation over a specified parameter range. For example, MIL-PRF-55310D defines frequency-temperature stability as follows:

> *6.4.16 Frequency-temperature stability.* The maximum permissible deviation of the oscillator frequency, with no reference implied, due to operation over the specified temperature range at nominal supply and load conditions, other conditions constant.

The short-term stability of an oscillator is measured by its Allan deviation, denoted by $\sigma_y(\tau)$, which is the square root of one half the average of the squares of the differences between successive average normalized frequency departure, averaged over the sampling time τ, under the assumption that there is no dead time between the averaged normalized frequency departure samples.